

Effects of pesticides on soil and water microflora and mesofauna in wetland ricefields: a summary of current knowledge and extrapolation to temperate environments

P. A. Roger^A, I. Simpson^B, R. Oficial^C, S. Ardales^C and R. Jimenez^C

^A Laboratoire de Microbiologie Orstom, Université de Provence, Case 87, 3 Place V. Hugo, 13331, Marseille Cedex 3, France.

^B NRI, Central Avenue, Chatham Maritime, Chatham, Kent, ME44TB, UK.

^C IRRI, PO Box 933, Manila, Philippines.

Summary. This review summarises information on the behaviour of pesticides and their impacts on microorganisms and non-target invertebrates that was collected in, or is applicable to, temperate wetland ricefields. An extensive bibliographic survey shows that current knowledge is fragmentary and partly outdated.

Pesticides applied on soil at recommended levels rarely had a detrimental effect on microbial populations or their activities. They had more effect on invertebrate

populations, inducing the blooming of individual species of floodwater zooplankton and reducing populations of aquatic oligochaetes in soil. Available information raises concerns regarding the long-term effects of pesticides on (i) microorganisms, primary producers, and invertebrates of importance to soil fertility, (ii) predators of rice pests and vectors, and (iii) microbial metabolism of pesticides.

Introduction

Modern technologies utilising optimum management practices, fertiliser-responsive varieties, fertilisers, and pesticides have increased wetland rice yield but have markedly modified traditional rice-growing environments. There is indirect evidence that crop intensification has decreased species diversity in ricefields (Roger *et al.* 1991), but other possible long- and short-term environmental impacts are not fully assessed. The greatest pressure exerted on the microbial, faunal, and floral communities of ricefields is due to fertiliser and pesticide use. Both have significant impact on population composition and dynamics. Therefore, it is important to understand and predict how agrochemicals, especially pesticides, may affect soil fertility through their effects on microorganisms responsible for maintaining soil fertility and the populations of invertebrates responsible for the recycling and translocating of nutrients. There is also concern about the increased use of pesticides, which may cause (i) environmental hazards such as watertable and water body contamination, (ii) biological imbalance in ricefield populations, and (iii) reduced efficiency because of shifts toward soil microorganisms more efficient in pesticide degradation.

We recently conducted a bibliographic survey of the impacts of pesticides on non-target microorganisms and

soil and water invertebrates in ricefields (Roger *et al.* 1994). A computerised database was established and quantitative data on pesticide persistence in rice soils and their effects on microorganisms were tabulated and analysed. This paper utilises this database for assessing or extrapolating the general trends of pesticide impacts on soil microorganisms and aquatic invertebrates in temperate rice environments.

Characteristics of the database

The bibliographic database on pesticide fate and impacts in tropical and temperate rice environments contains 547 references. Most studies were published during the 1980s, with very few published since 1990; as a result, no microbiological data are available for formulations recently adopted by rice growers (e.g. herbicides bensulfuron methyl and pendimethian).

Quantitative data were collected from 63 articles dealing with pesticide fate in ricefield soil, 71 articles dealing with pesticide impacts on nonphotosynthetic microorganisms, and 149 articles dealing with pesticide impacts on photosynthetic microorganisms (Table 1). Data were tabulated and general trends were analysed. Quantitative data on the impacts of pesticides on soil and water invertebrates, available in about 12 articles, were not numerous enough to be tabulated.

The data on pesticide fate and microbiological

11 AVR. 1995

ORSTOM Fonds Documentaire

N° 41.291 exp

Cote : B

M

Table 1. Numbers of reports using various methods for quantitative studies of pesticide in ricefields

Type of experiment	Fate of pesticides	Effect on photosynthetic microorganisms	Effect on nonphotosynthetic microorganisms
Cultures of microorganisms	0	130	2
Cultures of microorganisms with soil	1	6	0
Soil in test tubes or beakers	40	0	24
Pot experiments	8	3	21
Microcosms	6	0	0
Field experiments	8	10	14
Method not available	0	0	10
Total	63	149	71

impacts suffer from several biases and limitations. Most information on pesticide fate in ricefield soil arises from experiments with 20–100 g unplanted soil (Table 1), and this underestimates degradation because of the absence of rhizospheric effect and variations of environmental conditions (light, wind, temperature, redox potential). Microcosm studies easily lead to erroneous conclusions if environmental conditions are not properly reproduced (Higashi 1987). Field experiments are less numerous.

Quantitative estimates of the effects of pesticides on ricefield microorganisms or their activities are presented in 240 references from the database. The quantitative analysis and interpretation of this information are subject to caution for several reasons. (i) Organisms and pesticides studied do not constitute a representative sample of the numerous combinations occurring in ricefields. Data on photosynthetic microorganisms (149 references) are mostly on herbicides and cyanobacteria, and are more abundant than those on nonphotosynthetic microorganisms (71 references) (Table 1), which deal mostly with insecticides (see Table 2). (ii) Most studies are toxicity tests with algal cultures, or laboratory experiments with a few grams of soil. Less than 8% of quantitative studies were conducted *in situ*. Experiments with microbial cultures give an index of the strain's sensitivity to pesticides, but results cannot be extrapolated to field conditions where the initial concentrations of pesticides are likely to decrease rapidly because their degradation is enhanced by soil microflora, nonbiological decomposition, leaching, volatilisation, and soil adsorption. Concentrations of pesticides that affect microorganism growth depends on the initial microbial population, its nutrient status, the method of pesticide application, and the degradation products. These factors markedly differ *in vitro* and *in situ*. (iii) Many studies used pesticide concentrations higher than those resulting from the recommended level for field application (RLFA). Our database tabulates 1045 quantitative data on pesticides effects on photosynthetic microorganisms, among which 638 were obtained at concentrations twice as high as

RLFA, probably because studies aimed at establishing lethal concentrations for the strains, rather than the possible effects *in situ*. Such data are of little value for drawing conclusions, except when no effect was recorded. It is worth noting, however, that concentrations higher than RLFA may occur in the field because of uneven distribution of pesticide due to the formulation used (i.e. granules) or the method of application (i.e. double application at the edge of the field).

Pesticide behaviour in wetland ricefields

General characteristics of pesticide behaviour in wetland soils

In ricefields, as in any agricultural ecosystem, pesticide fate is governed by transfer and degradation processes. The presence of floodwater and puddled soil accelerates pesticide dilution. If a pesticide applied on a nonflooded soil remains in the surface 2 cm, 1 kg/ha of active ingredient (a.i.) corresponds to 5 mg/kg soil (dry weight) for a bulk density of 1 Mg/m³. With a water-soluble pesticide distributed in 10 cm water and 10 cm puddled soil, 1 kg a.i./ha corresponds to 0.4 mg/kg. Pesticide degradation in ricefields is favoured by reducing conditions, and by temperature and pH ranges favouring microbial activity. Volatilisation is favoured by high temperature and by gas exchange occurring between soil and atmosphere through the rice plant (Siddaramappa and Watanabe 1979). As a result, pesticide persistence is often less in flooded than nonflooded soils. Our database on half-life of pesticides in rice soils shows that only 8 tests of 45 reported half-lives shorter in nonflooded than in flooded soils (Fig. 1a).

A usually longer persistence of pesticides in sterilised soils demonstrates the importance of microbial degradation (Fig. 1b). In nonflooded cultivated soils, bacteria and fungi are considered to be mainly responsible for pesticide transformations. In wetlands, fungi are probably less important, whereas the role of algae may be significant as shown for parathion (Sato and Kubo 1964). Repeated application of a pesticide can enhance the growth of the specific decomposing

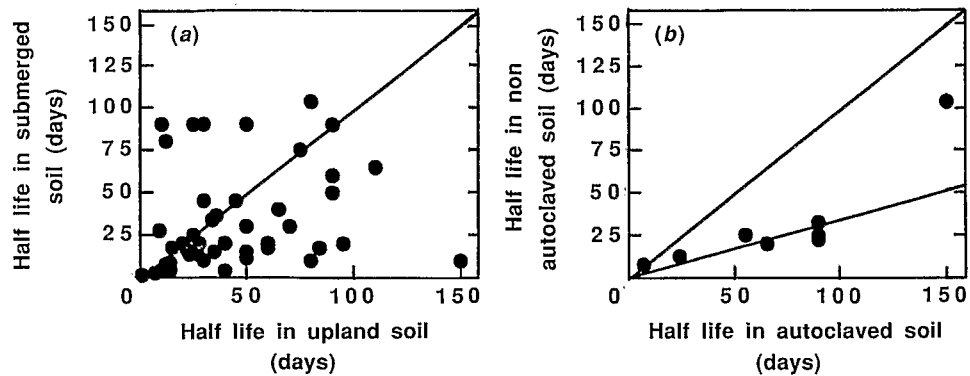


Figure 1. Comparison of the half-life of (a) 36 pesticides in submerged and upland soils and (b) 9 pesticides in autoclaved and non-autoclaved flooded soils.

microorganisms and reduce its persistence, as observed for lindane, diazinon, and aldicarb (Read 1987), but not carbofuran and benthocarb (see Roger *et al.* 1994). Bacteria able to degrade specific pesticides were isolated from tropical and temperate (Watanabe 1978) ricefields previously treated with these pesticides. Repeated application was also reported to change the metabolic pattern of decomposition in both tropical and temperate (Moon and Kuwatsuka 1984) ricefields. With benthocarb, this led to phytotoxicity problems. This herbicide is generally detoxified by hydrolysis, but its repeated application to flooded soil favoured the multiplication of anaerobic bacteria that decompose it by reductive dechlorination, resulting in the formation of phytotoxic S-benzyl N, N-diethylthiocarbamate, causing dwarfing of rice (Nishio 1984).

Comparison between tropical and temperate conditions

Climate is the major factor likely to cause differences in pesticide behaviour in temperate and tropical rice. Pesticide photo-decomposition, volatilisation, and microbial degradation are expected to be slower in temperate conditions because of lower light intensities and temperatures. Moreover, when soil temperature decreases, the adsorption of pesticides by soil increases. This may result in lower concentrations of pesticides dissolved in soil solution and floodwater and their slower disappearance, as shown for DDT by Guenzi and Beard (1976). However, very few data comparing pesticide half-life under tropical and temperate conditions are available to verify this hypothesis. Yuh-Lin Chen (1980) reported that butachlor half-life in floodwater was 20 h in hot, cloudless weather, and 5.5 days in cold, cloudy weather. Gamma hexachlorocyclohexane (HCH) decomposed faster at 35°C than at 25°C in a flooded soil (Yoshida and Castro 1970).

Straw and organic matter incorporation, which increases microbial activity and hastens the drop in redox

potential in flooded soils, is known to favor pesticide degradation in wetland soils (Ferreria and Raghu 1981; Chopra and Magu 1986). Currently, burning is the main method of handling rice straw. Environmental policies tending to restrict straw burning and to promote incorporation might be adopted more rapidly in temperate developed countries than in the tropics.

Alternate periods of flooding and drying, resulting in successions of aerobic and anaerobic microflora, favour extensive microbial decomposition of pesticides. Sethunathan (1972) showed that diazinon was hydrolysed in flooded soils, but the pyrimidine ring of its hydrolysis products was open only under aerobic conditions following anaerobiosis. In irrigated tropical ricefields, crop intensification might lead to long periods of continuous flooding, which favors the decomposition of many, but not all, pesticides (Fig. 1a). In particular, the half-lives of buprofezin (Funayama *et al.* 1986), benthocarb (Nakamura *et al.* 1977), and heptachlor and metoxychlor (Castro and Yoshida 1971) are much shorter in nonflooded than in flooded conditions. In temperate ricefields, with a single crop per year, the alternation of flooded and nonflooded conditions probably allows better decomposition of a broader range of pesticides than continuous flooding. However, no field study has yet compared pesticide decomposition under both water management regimes.

Other factors affecting pesticide fate, such as soil properties and the method of pesticide application, are unlikely to differ between temperate and tropical environments to a degree that would cause marked differences in pesticide behavior.

Effects on nonphotosynthetic microorganisms

Role of nonphotosynthetic microorganisms in ricefields

Nonphotosynthetic microorganisms are the agents of nutrient recycling and maintenance of soil fertility. In particular, the nitrogen (N) fertility of rice soils partly

results from the balance between activities of various populations that (i) transform organic N to forms available to rice (mineralising microflora, ammonifiers, nitrifiers), (ii) provide inputs of N through biological N₂ fixation (BNF) (heterotrophic N₂ fixers in the bulk of soil and the rhizosphere), and (iii) cause gaseous losses of N (denitrifiers) (Roger *et al.* 1993). Recent results have shown that, at the levels of inorganic fertiliser usually applied in ricefields, most N absorbed by the plant originates from soil where it is released by the turnover of a microbial biomass which, in terms of N content, represents only a few per cent of total soil N (Watanabe *et al.* 1988).

General trends

The database tabulates 606 quantitative records of pesticide effects on population densities of nonphotosynthetic microorganisms and their major activities (respiration, N and C mineralisation, biological N₂ fixation, nitrification, denitrification etc.), mostly measured in the presence of soil (Table 2). Many more data refer to pesticides used with tropical rice (509) than with temperate rice (97). Effects were negative in 20% of cases (tropical 20%, temperate 19%), not significant in 60% of cases (58 and 68%), and positive in 20% of cases (22 and 13%). As the dataset on temperate rice is too small to allow comparisons, further discussion is on the whole dataset.

Field experiments showed a higher percentage of nonsignificance (n.s.) than small scale experiments (73 v. 46%), confirming that the latter overestimate pesticide effects. Extreme effects (all negative or all positive) were also less frequent in the field. Pesticide effects were more marked in the bulk of soil than in the rhizosphere (n.s. 52 v. 70%), which, because of denser microbial populations and continuous nutrient supply through root exudation, is a more active, and probably more resilient, environment than the bulk of the soil. Herbicides affected more microorganisms or their activities than did fungicides (n.s. 30 v. 50%) or insecticides (68%). When a significant effect was observed, similar percentages of increase and decrease in population density or activity was observed for insecticides (36% decrease, 35% increase) and for herbicides (17% decrease, 16% increase), while with fungicides an increase was more frequent (5% decrease, 45% increase). Population densities were less affected by pesticides (n.s. 58%) than were microbial activities (n.s. 46%). Soil enzymes were very little affected (n.s. 93%). Fungi and actinomycetes were less sensitive to pesticides than were bacteria (n.s. 80 and 62 v. 52%).

Effects on nitrogen cycle

Nitrogen-fixing microorganisms and BNF were more affected by pesticides than were other populations and activities of the N cycle (n.s. 31 v. 71%) (Table 2). With

25% negative effects and 45% positive effects, BNF seems quite versatile in its response to pesticides. One pesticide could produce negative or positive effect depending on soil type. Nayak and Rajaramamohan Rao (1980) observed positive effects on BNF of benomyl, a carbamate fungicide, when applied to alluvial, laterite, and acid sulfate soils, and of carbofuran, a methylcarbamate insecticide, when applied to alluvial, laterite, and acid saline soils. Gamma-BHC stimulated BNF in alluvial and acid sulfate soils but inhibited it in other soils. The authors explained these results by differential responses of specific groups of N₂-fixing organisms to the pesticides, depending on the soil type. A general trend is that, when significant, effects of pesticides on non-photodependent BNF were more often positive than negative.

Nitrification was not affected by pesticides in 60% of cases. Negative effects of pesticides on nitrification, observed in 34% of cases (Table 2) cannot be considered detrimental, as reducing nitrification also reduces N losses by denitrification. Identifying efficient and economically feasible nitrification inhibitors has been an objective of the research into microbial management in ricefields (Roger *et al.* 1993). Denitrification was not affected by pesticides in 87% of cases, probably because the denitrifying microflora, being complex and very versatile, can metabolise or resist a wide range of substrates. As a result, high pesticide levels are needed to inhibit denitrification. For example, pot and laboratory experiments by Mitsui *et al.* (1964) showed that 20–100 µg/g of dithiocarbamate compounds was required to decrease denitrification in an alluvial ricefield soil. This probably explains why research aiming at decreasing N fertiliser losses is focused on urease and nitrification inhibitors rather than denitrification inhibitors (Roger *et al.* 1993).

Field experiments

Pesticide effects on nonphotosynthetic microorganisms were less often significant in the field than *in vitro* and were more often negative than positive, whereas the same percentage of positive and negative effects (20%) was recorded with the whole dataset (Table 2). However most trends observed with the whole dataset were also observed *in situ*, namely (i) more impact of herbicides than of insecticide; (ii) greater sensitivity to pesticides observed in bacteria than in fungi, actinomycetes, or algae; (iii) greater sensitivity to pesticides observed in microbial activities than in population densities; and (iv) greater sensitivity to pesticides observed for BNF than the average sensitivity estimated from all *in situ* data (39 v. 73%).

Results of field experiments usually indicate either an absence of pesticide effect or a transitory change of population densities, followed by recovery within 2–3 weeks. However, a long-lasting stimulation of rhizospheric BNF was observed in the field at 55 days (Rao *et al.* 1983) and 87 days (Mahapatra and Rao 1981)

Table 2. Per cent of experiments in each 'effect' category, for experiments considering pesticide effects on nonphotosynthetic ricefield microorganisms at concentrations corresponding to the recommended level for field application (adapted from Roger *et al.* 1994)

Most experiments were bacterial counts and activity measurements performed several times after pesticide application; each experiment was attributed a score within a 5-cases scale: no effect, no significant difference between treatment and control; all negative/positive, for all measurements the treatment was statistically lower/higher than the control; negative/positive trend, various effects were recorded, the balance was negative/positive

Groups	No. of data sets	Effect category				
		All negative	Negative trend	No effect	Positive trend	All positive
All data						
Experimental design (606 data)						
Field experiments	309	5	17	73	4	1
Pot and flask experiments	283	10	8	46	18	19
Environment (590 data)						
Tropical soil	509	6	14	58	12	10
Temperate soil	97	18	1	68	6	7
Soil	347	7	12	52	16	14
Rhizosphere	243	8	13	70	5	5
Type of measurement (606 data)						
Microbial counts	249	10	10	58	13	9
Bacteria	175	13	9	52	15	11
Actinomycetes	37	3	19	62	8	8
Fungi	37	5	5	81	8	0
Microbial activities	225	8	18	46	13	15
Enzymatic activities	123	0	7	93	1	0
Pesticide group (600 data)						
Fungicides	58	5	0	50	24	21
Herbicides	102	13	23	30	21	14
Insecticides	440	6	11	68	7	8
Total	606	8	12	60	11	9
Nitrogen cycle						
Data on BNF	176	2	23	31	26	19
In bulk of soil	95	1	12	25	37	25
In rhizosphere	81	2	36	38	12	11
Bacterial counts	69	4	3	52	23	17
BNF measurements	107	0	36	18	27	20
Fungicides	25	0	0	20	52	28
Herbicides	26	0	23	23	35	19
Insecticides	125	2	27	35	18	17
Other aspects of N cycle	126	16	6	71	3	5
Nitrification	54	30	4	61	0	6
Denitrification	47	6	4	87	2	0
Others	25	4	12	60	12	12
Total	302	8	15	48	16	13
In situ measurement						
Herbicides	50	8	18	64	10	0
Insecticides	297	4	14	75	4	3
Bacteria	84	17	13	57	6	7
Actinomycetes	29	0	24	76	0	0
Fungi	29	0	7	86	7	0
(Algae and cyanobacteria) ^A	42	7	10	71	10	2
Microbial counts	184	9	13	68	6	4
Microbial activities	65	0	45	46	8	2
Heterotrophic BNF all data	93	2	32	39	15	12
Bacterial counts	35	6	6	63	3	23
BNF measurements	58	0	48	24	22	5
Total	351	5	16	73	5	2

^A Forty-two data sets on microalgae and cyanobacteria are included for comparison.

after HCH application and was correlated with a retarded drop in redox potential of the rhizosphere soil, which favored the growth of populations of *Azospirillum* and *Azotobacter* (Mahapatra and Rao 1981). The only field study conducted over several crop cycles in temperate conditions (Nishio and Kusano 1978) showed that nitrification and total bacterial populations in soils that received fenitrothion or malathion for 4 consecutive years were not significantly different from those in soils where no insecticide was applied, but counts of bacteria tolerant to organophosphate insecticides were 2–4 times higher in treated soils.

Soil microbial biomass is regarded as a major channel through which nutrients are transferred to rice (Watanabe *et al.* 1988). Field surveys of 32 rice farms in the Philippines (Roger *et al.* 1994) showed no correlation between soil microbial biomass estimated at the beginning and the end of the crop cycle (to assess long-term effects of pesticides) and various expressions of the intensity of pesticide utilisation.

Effects on photosynthetic microorganisms

Role of photosynthetic microorganisms in ricefields

Photosynthetic microorganisms, mostly cyanobacteria and microalgae, are major components of the photosynthetic aquatic biomass that develops in ricefield floodwater and includes macrophytic algae and vascular macrophytes. Reported average primary production in ricefield floodwater over a crop cycle ranges from 0.5 to 1 g carbon (C)/m².day. The yield of standing crops of photosynthetic organisms in floodwater ranges from 100 to 500 kg DW/ha (Roger and Kurihara 1991).

Photosynthetic aquatic microorganisms trap atmospheric C and N, in addition to C and N evolved from the soil, and help to reduce nutrient losses when reincorporated into the soil. They affect N fertility of ricefields through: (i) photodependent biological N₂ fixation (BNF) by cyanobacteria, which provides

5–20 kg N/ha.crop, depending on the method of N fertiliser application (Roger *et al.* 1993); (ii) N immobilisation and recycling in relation with weeding, death or grazing, followed by decomposition, N accumulation at soil surface, and translocation to deeper soil by soil fauna (Roger and Kurihara 1991); (iii) replenishment of the soil microbial biomass and available N, as shown by positive correlations between these variables and chlorophyll-type compounds (Watanabe and Inubushi 1986); (iv) provision of N to the rice plant, which averages 30% of the N of cyanobacteria, algae, and aquatic plants incorporated into soil and 20% of those decomposing at the soil surface (Roger and Kurihara 1991); and (v) induction of N losses by NH₃ volatilisation (2–60% of N applied), partly due to algae, which deplete CO₂ in floodwater, increasing its pH and the concentration of volatile NH₃ (Fillery *et al.* 1986).

In transplanted rice, microalgae and submerged and floating plants are rarely considered weeds of major economic importance. In direct-seeded rice, microalgae and macrophytic algae are detrimental at germination because they compete for light, they form a membranaceous mat restricting penetration of the rice roots into the soil and the gaseous exchange between soil and water, and they have detrimental mechanical effects on the rice when epiphytic growth of these weeds either pulls seedlings down, or lifts them up and uproots them, with varying water level (Smith *et al.* 1977; Noble and Happey-Wood 1987).

Impacts of pesticides on algae and cyanobacteria

Quantitative data on the impacts of pesticides on ricefield algae and cyanobacteria available in the literature are mostly percentages of inhibition estimated by measuring dry weight, N content, chlorophyll content, etc. on laboratory cultures. The analyses of 407 experimental records at RFLA (Table 3) confirms that pesticide effects are more marked *in vitro* than in the field.

Table 3. Per cent of experiments in each 'level of inhibition' category, for experiments considering pesticide effects on photosynthetic ricefield microorganisms (cyanobacteria and microalgae) at concentrations corresponding to the recommended level for field application (adapted from Roger *et al.* 1994)

Type of data	No. of data sets	Levels of inhibition				
		None	<50%	50%	>50%	100%
All data	407	39	19	26	2	14
All data <i>in situ</i> or with soil	39	62	8	3	3	26
Algicides (3 tested)	33	3	0	67	0	30
Fungicides (22 tested) ^A	30	40	10	7	0	43
Herbicides (57 tested)	252	33	25	28	2	12
Herbicides, <i>in situ</i> or with soil	24	58	8	4	4	25
Insecticides (28 tested)	97	67	11	14	3	4
Insecticides, <i>in situ</i> or with soil	10	90	10	0	0	0

^A Several fungicides act also as algicides.

Herbicides were most detrimental to phytoplankton, causing partial or total inhibition in 67% of the tests *in vitro* and 42% of the tests in the field or performed with soil. Herbicides can inhibit photodependant BNF by cyanobacteria, as shown with pentachlorophenol (PCP) (Ishizawa and Matsuguchi 1966). Some herbicides affect specifically the N₂-fixing ability of cyanobacteria: inhibition occurred in N-free medium but not in the presence of inorganic N, as observed with dichlone (fungicide–algicide) and butachlor (Kashyap and Pandey 1982).

With insecticides, no inhibition was observed for 67% of all data and 90% of field data.

Field studies in temperate areas have shown various effects of pesticides on phytoplankton. (i) Phytoplankton abundance decreases (Takamura and Yasuno 1986). (ii) Phytoplankton biodiversity decreases (Tomaselli *et al.* 1987). (iii) Selective toxicity affects the composition of the algal population. Many cyanobacteria can tolerate pesticide levels higher than the RFLA, and are more resistant to pesticides than are eucaryotic algae, which results in selection of cyanobacteria. This was observed with BHC (Ishizawa and Matsuguchi 1966) and PCP (Watanabe 1977). (iv) There is a short-term, indirect, growth-promoting effect of insecticides due to the inhibition of invertebrates that graze on algae and cyanobacteria, as observed with carbofuran, phorate, and parathion (Hirano *et al.* 1955). However, insecticide application did not invariably increase photodependant BNF. Some inhibitory effect was reported for PCP *in situ* (Ishizawa and Matsuguchi 1966). (v) There is a long-term, indirect, inhibitory or selective effect on phytoplankton by decreasing the populations of predators of grazers and allowing the proliferation of grazers resistant to insecticides, which then develop much denser populations than when biodiversity was high and grazers were controlled by predation (Takamura and Yasuno 1986). Grazing is a major limiting factor to photodependant BNF in ricefields by inhibiting cyanobacteria populations growth or leading to the dominance of mucilaginous cyanobacteria, which are usually more resistant to grazing than but less active in BNF (Roger *et al.* 1993). The growth of mucilaginous cyanobacteria might also be especially detrimental to direct-seeded rice because such strains have an ability to grow epiphytically (Roger *et al.* 1981) and to cause damage to young seedlings.

Specific aspects pertaining to temperate rice

Whereas in the tropics, studies on phytoplankton have focused on the use of N₂-fixing cyanobacteria as biofertiliser, in temperate regions, studies have dealt mostly with phytoplankton's detrimental effects: pulling down or uprooting rice seedlings, and favouring N-fertiliser losses through NH₃ volatilisation.

Blooms of unicellular algae, which may damage

young seedlings at the beginning of the crop cycle in direct-seeded rice, are most often controlled by copper-based algicides (Noble and Happey-Wood 1987). Copper use against algae in ricefields is documented mostly in temperate areas of Russia (Kayumov 1963), Italy (Bisiach 1971), the USA (Dunigan and Hill 1978), and Australia (Noble and Happey-Wood 1987). As cyanobacteria are often more resistant to pesticides than are eucaryotic algae, algicide application to control unicellular eucaryotic algae may cause blooming of cyanobacteria as observed in Italian ricefields (Bisiach 1970). In Australian ricefields it was also noted that detrimental blooms of unicellular algae may result from the utilisation of insecticides applied against chironomid larvae, which might damage rice roots but are also algal grazers. After insecticide application was discontinued, algal growth remained at a level not detrimental to young rice seedlings (Noble and Happey-Wood 1987).

Algicides tested for their potential to decrease N fertiliser losses by NH₃ volatilisation are copper sulfate (Muirhead *et al.* 1990), simazine (Vlek *et al.* 1980), diuron (IRRI 1977), and terbutryne (Bowmer and Muirhead 1987). Simazine, diuron, and terbutryne reduced pH, thereby increasing NH₄⁺ concentration in floodwater, establishing conditions less favorable for NH₃ volatilisation, but data suggested that fertiliser saving was low (Muirhead *et al.* 1990). With terbutryne, the estimated saving averaged 4.7–9.6 kg N/ha when 90–150 kg N/ha was applied. Deep placement of N fertiliser to avoid algal blooming and prevent high concentration of NH₃ in water seems a more efficient method to decrease N losses by volatilisation (Roger *et al.* 1993). Floodwater pH is fairly stable under floating macrophytes such as *Azolla* and *Lemna* because they prevent light penetration through water. Herbicide application on such mats may increase photosynthetic activity in floodwater by resistant microalgae and enhance N losses by volatilisation (Roger *et al.* 1993).

Effects on invertebrates

Soil and water invertebrates dominant in ricefields are ostracods, copepods, cladocerans, rotifers, insect larvae, aquatic insects, molluscs, oligochaetes, and nematodes (Roger and Kurihara 1991). Representatives of all these groups are present in tropical and temperate ricefields, where they have agricultural impact as nutrient recyclers, rice pests, and rice pest predators, and environmental impact as vectors of human and animal diseases.

Microcrustaceans and larvae of mosquitoes and chironomids are ubiquitous primary consumers that recycle nutrients from the photosynthetic aquatic biomass. They usually proliferate about 2 weeks after the peak of phytoplankton abundance (Kurasawa 1956) and may cause the disappearance of microalgae blooms within 1–2 weeks. Ostracods have the potential to recycle 20 kg N/ha.crop. Primary consumers that feed

on cyanobacteria may inhibit photodependent BNF or cause the dominance of mucilaginous colonial forms that are less susceptible to grazing than noncolonial forms but are less active N_2 fixers (see Roger and Kurihara 1991). Large populations of microcrustaceans were recorded in Japan (Kurasawa 1956; Kikuchi *et al.* 1975). Species of Ostracods originating from Africa, Asia, South America, and Australia were recorded in Italian ricefields (Fox 1965; Ghetti 1973). Chironomids were reported to be the most numerous insects in the ricefields of Korea, and up to 18000 larvae/m² were recorded in California (Clement *et al.* 1977). Oligochaetes, especially tubificidae, are a major component of the zoobentos which ensures nutrient exchange between soil and floodwater and increases soil N uptake by rice plants. Populations range up to 40000/m² (0–700 kg fresh weight/ha) in temperate (Kikuchi *et al.* 1975) and tropical ricefields (Simpson *et al.* 1993a, 1993b).

Invertebrates also have detrimental effects. Mosquitoes are vectors of diseases including malaria and Japanese encephalitis. Chironomids and ostracods feed on rice seedling roots, but this effect is limited in time and space (Clement *et al.* 1977; Barrion and Litsinger 1984). Large species of snails which graze on rice seedlings have been recognised as an important rice pest in tropical countries and Japan. Other species (*Bilinus* spp., *Biomphalaria* spp., *Limnea* spp.) are vectors of bilharziosis.

Impact of pesticides

Methodological aspects. Field experiments using farmer practices and pesticide rates corresponding to RFLA are scarce. Those testing pesticides with no fertiliser application are of limited value because such a situation is uncommon in farmer's fields, and zooplankton are more affected by fertiliser than by pesticides (Simpson *et al.* 1994b). Few records of floodwater biota dynamics during a crop cycle and under a range of agricultural practices are available for temperate (Kurasawa 1956; Ishibaschi and Itoh 1981; Takamura and Yasuno 1986) and tropical ricefields (Simpson *et al.* 1993a, 1993b, 1994a, 1994b, 1994c).

In vitro effects of pesticides. Effects of pesticides applied to ricefields on soil and water fauna include acute toxicity, alteration of filtration and assimilation, and inhibition of growth and egg production. Insecticides are the most active pesticides on floodwater invertebrates. Herbicides and fungicides appear to possess limited toxicity to invertebrates at field concentrations (Georghiou 1987).

Zooplankton. The major reported effects of insecticide application on zooplankton are a transient decrease of the total population, a decrease in species diversity, and the blooming of individual species, especially ostracods, mosquito larvae, and molluscs

(Roger and Kurihara 1991). A field study by Takamura and Yasuno (1986) showed the development of large populations of chironomids and ostracods in herbicide and insecticide treated fields. Simultaneously, the number of natural predators of chironomids and ostracods decreased. Benthic algae decreased in herbicide-treated plots and did not increase in insecticide-treated plots, probably because of grazing by ostracods. Lim and Wong (1986) attributed the dominance of ostracods in treated fields to their resistance to pesticides and the large number of eggs produced parthenogenetically. In Japan, Takaku *et al.* (1979) observed that the application of fenitrothion by helicopter heavily reduced the abundance of *Moina* sp. in floodwater.

Whereas insecticides appear to favor ostracods, an almost complete inhibition of ostracods for the whole crop cycle after benthocarb application was observed by Ishibashi and Itoh (1981) in Japan. There are also reports indicating a limited effect of pesticides on zooplankton. In a 2-year field study of the effects of carbofuran at high levels of N fertiliser, Simpson *et al.* (1994b) concluded that aquatic invertebrates were not strongly affected.

Vectors. Most agricultural insecticides are nonspecific. They affect rice pests as well as vectors, on which they have 3 major effects: temporary decrease in incidence, resurgence of resistant strains, and adverse effects on predators and competitors (see Roger and Bhuiyan 1990). Marked reduction of malaria and Japanese encephalitis in Japan since 1945 results, at least partly, from the extensive use of organophosphorus and carbamate insecticides. The decrease of *Culex tritaeniorhynchus* after 1970 in Japan might partly result from the increase in natural predators by the switch from chlorinated hydrocarbons to carbamates, less toxic to vector predators (Mogi 1987). In Korea, agricultural pesticide application reduced the density of *C. tritaeniorhynchus*, the vector of Japanese encephalitis, in rice-growing areas, but had no effect on the malaria vector *Anopheles sinensis*. Mosquito populations are particularly good at evolving resistant strains: in 1987, 50 malaria vectors resistant to 1 or more pesticides were recorded in the world (Bown 1987).

Aquatic oligochaetes. A few data indicate that aquatic oligochaetes are sensitive to pesticides, but they are not numerous enough to draw conclusions. In Japan, the appearance of significant densities of tubificids in an experimental ricefield studied for 9 years was attributed to the replacement of PCP by benthocarb and the pollution of the irrigation water by domestic sewage. Simultaneously, grain yield increased by 0.9 t/ha (Kurihara and Kikuchi 1988). In the Philippines, carbofuran, butachlor, and triphenyl tin hydroxide applied together at the beginning of the crop reduced

average populations over the crop cycle from 1760 to 200/m² (Roger *et al.* 1994). In a 2-year study, carbofuran application decreased aquatic oligochaetes during the first crop cycle, but not during the second year, when the same treatment was applied (Simpson *et al.* 1993a).

Ishibaschi and Itoh (1981) found no significant effect of the herbicide benthocarb on average populations of saprophytic and parasitic nematods counted on 14 occasions during a crop cycle.

Molluscs. Snails are not usually affected by conventional rice pesticides but their populations may increase because of reduced competition for energy sources. After harvest, Ishibashi and Itoh (1981) observed larger populations of snails in fields previously treated with benthocarb than in the untreated control. Simpson *et al.* (1994c) found limited evidence suggesting that snails were favored by carbofuran or butachlor application.

Conclusions

Many papers on pesticide fate and impacts in wetland rice were published between 1970 and 1985. The number of papers has decreased greatly during the last 5 years. Studies have dealt mostly with tropical environments and focus on the effects of insecticides on heterotrophic microorganisms and invertebrates, and herbicides on cyanobacteria. Information on pesticide impacts in temperate rice is limited and extrapolation from data obtained in the tropics should be done with caution because the main class of pesticides used in rice culture in tropical areas is insecticide, and in temperate areas is herbicide; also, many chemicals and formulations currently used differ from those studied in the tropics in 1970–85.

It is recognised that tropical flooded soil is an environment favorable for rapid detoxification of many pesticides. In temperate ricefields, lower temperatures might slow decomposition during the crop cycle, whereas the dry fallow might favor residue mineralisation.

Field and laboratory studies showed that pesticides applied to soil at recommended levels rarely had a detrimental effect on microbial populations or their activities. When significant changes were observed, a recovery of populations or activities was usually observed after 1–3 weeks. This seems partly to confirm the common belief that pesticides applied at recommended levels and intervals are seldom deleterious to the beneficial microorganisms and their activities (Wainright 1978).

Invertebrates seem to be more sensitive to pesticides than microorganisms. In the case of floodwater invertebrates, pesticide use can lead to the blooming of individual species (especially primary consumers) that might be detrimental. Reports in temperate and tropical

ricefields indicate that aquatic oligochaetes in soil are at least partly inhibited by pesticide use. However, it is important to emphasise that impacts of pesticides on the soil–floodwater ecosystem can be significant without being detrimental. For example, a shift in algal community structure may not affect soil fertility, providing that aquatic primary production is unchanged. Impacts should be considered in the context of the ecosystem equilibrium and not in isolation. Except for vectors and major rice pests, many invertebrates have both beneficial and detrimental effects. For example, chironomid larvae are detrimental when they feed on rice roots and N₂-fixing cyanobacteria, but they are useful because they recycle nutrients and serve as an alternative food for predators of rice pests, and thus, help in conserving them (Yatsumatsu *et al.* 1979).

Available information raises several concerns regarding long-term impacts of pesticides on soil fertility, the microbial metabolism of pesticides, and the preservation of a biological equilibrium in the floodwater to avoid proliferation of detrimental invertebrates. There are reports of significant direct or indirect effects of pesticides on microorganisms, primary producers, and floodwater invertebrates of importance to soil fertility. Possible long-term impacts are largely unknown. Several long-term experiments have shown a yield decline with time (Cassman and Pingali 1993). Reasons are unclear, but one factor might be the combination of weeding and herbicide use, and a dense rice canopy, which restricts the growth of the photosynthetic aquatic biomass and, in turn, its contribution to the replenishment of soil microbial biomass and N-fertility. Insecticides are also possibly involved, by decreasing populations of aquatic oligochaetes and through the translocation of nutrients accumulating at the soil surface to the deeper soil layer. Few data are available to substantiate this hypothesis, but experiments at IRRI have shown that totally restricting photosynthetic activity in floodwater of planted fields with black cloth coverage reduced soil microbial biomass by 22% after 2 years.

Pesticides might have only temporary effects but, when applied repeatedly, could lead to the promotion, depression, or disappearance of components of the microbial community, thus leading to a new equilibrium and to changes in the rate or pattern of their microbial decomposition that might be detrimental.

A better understanding of floodwater ecology is needed to develop agricultural practices that maintain a biological equilibrium in the ricefield ecosystem; in particular, practices that decrease pesticide use and conserve the natural predators of rice pests and vectors. Even if it is not envisaged that invertebrate predators can be exploited as biological control agents, cultural practices favoring their conservation—which is a major

component of integrated pest and vector management—should be encouraged.

It would be as unwise to under- or over-estimate the significance of pesticide impacts on microorganisms and non-target invertebrates in wetland soil. Underestimation could cause avoidable ecological damage. Overestimation could restrict the judicious use of pesticide when appropriate. Current knowledge of impacts in temperate ricefields is fragmentary and this area needs further investigation. Study of the fate and effects of pesticides, hitherto mostly restricted to short-term laboratory conditions, must be performed under more realistic field conditions and cultural practices, and on a long-term basis.

Acknowledgments

This work was conducted under scientific agreements between IRRI and ORSTOM (France), and IRRI and NRI (UK).

References

- Barrion, A. T., and Litsinger, J. A. (1984). Chironomid, corixids and ostracod pests of irrigated rice seedling roots. *International Rice Research Newsletter* 9, 19.
- Bisiach, M. (1971). Laboratory algicidal screening for the control of algae in rice. *Riso* 21, 43–58.
- Bowmer, K.H., and Muirhead, W. A. (1987) Inhibition of algal photosynthesis to control pH and reduce ammonia volatilization from rice floodwater. *Fertilizer Research* 13, 13–29.
- Bown, D. N. (1987). Agricultural use of pesticides and their effect on vector-borne disease transmission in the WHO region of the Americas. In 'Effect of Agricultural Development on Vector-Borne Diseases.' Proceedings 7th Annual Meeting of the Joint WHO/FAO/UNEP PEEM, 7–12 Sept. 1987. pp. 53–6. (FAO: Rome.)
- Cassman, K. G., and Pingali, P. L. (1993). Extrapolating trends from long-term experiments to farmer fields: the case of irrigated rice systems in Asia. In 'Proceedings of the Working Conference on Measuring Sustainability using Long-Term Experiments.' (Rothamstead Experimental Station: Rothamstead, U.K.)
- Castro, T. F., and Yoshida, T. (1971). Degradation of organochlorine insecticides in flooded soils in the Philippines. *Journal of Agriculture and Food Chemistry* 19, 1168–70.
- Chopra, P., and Magu, S. P. (1986). Respiration as influenced by urea herbicides in soil amended with compost. *International Journal of Tropical Agriculture* 4, 137–42.
- Clement, S. L., Grigarick, A. A., and Way, M. O. (1977). The colonisation of California rice paddies by chironomid midges. *Journal of Applied Ecology* 14, 379–89.
- Dunigan, E. P., and Hill, V. (1978). Studies on the use of chemicals to control algal surface blooms in rice floodwaters. In 'Louisiana Agricultural Experiment Station Reports on Projects for 1977.' pp. 153–6. Baton Rouge, LA, USA.
- Ferreria, J., and Raghu, K. (1981). Decontamination of hexachlorocyclohexane isomers in soil by green manure application. *Environmental Technology Letter* 2, 357–64.
- Fillery, I. F. G., Roger, P. A., and De Datta, S. K. (1986). Ammonia volatilization from nitrogen sources applied to rice fields, Part 2: Floodwater properties and submerged photosynthetic biomass. *Soil Science Society of America Journal* 50, 86–91.
- Fox, H. M. (1965). Ostracod crustaceans from ricefields in Italy. *Memoriae del Istituto Italiano di Idrobiologia Dottore Marco Marchi* 18, 273–94.
- Funayama, S., Uchida, M., Kanno, H., and Tsuchiya, K. (1986). Degradation of buprofezin in flooded and upland soils under laboratory conditions. *Journal of Pesticide Science* 11, 605–10.
- Georghiou, G. P. (1987). The effect of agrochemicals on vector populations. In 'Effects of Agricultural Development on Vector-Borne Diseases.' AGL/MISC/12/87. pp. 101–6. (FAO: Rome.)
- Ghetti, P. F. (1973). Dynamique des populations d'Ostracodes de douze rizières italiennes: notes d'écologie. *Annales de la Station Biologique de Besse en Chandesse* (France) 7, 273–94.
- Guenzi, W. D., and Beard, W. E. (1976). The effects of temperature and soil and water on conversion of DDT to DDE in soil. *Journal of Environmental Quality* 5, 243–6.
- Higashi, R. M. (1987). Modeling the environmental fate of rice herbicides. IRRI Library SB249 H54. pp. 1–109.
- Hirano, T., Shiraishi, K., and Nakano, K. (1955). Studies on the blue-green algae in lowland paddy soil. Part I. On some conditions for the growth of BGA in paddy soils and its effect on growth of rice plant [in Japanese]. *Shikoku Nogyo Shikenjo Hokoku* 2, 121–37.
- IRRI (1976). International Rice Research Institute Annual Report for 1976. (IRRI: PO Box 933, Manila.)
- Ishibashi N., and Ito, S. (1981). Effects of herbicide benthocarb on fauna in paddy field [in Japanese] *Proceedings of the Association for Plant Protection, Kyushu* 27, 90–3.
- Ishizawa, S., and Matsuguchi, T. (1966). Effects of pesticides and herbicides upon microorganisms in soil and water under waterlogged condition. *Bulletin of the National Institute for Agricultural Sciences B* (Japan) 16, 1–90.
- Kashyap, A. K., and Pandey, K. D. (1982). Inhibitory effects of rice-field herbicide Machete on *Anabaena doliolum* and protection by nitrogen sources. *Zeitschrift für Pflanzenphysiologie* 107, 339–46.
- Kayumov, V. (1963). Use of copper sulfate for control of algae on rice fields. *Kolkhoz Sovkhoz Proizv Turkmenistana* 6, 37–8.
- Kikuchi, E., Furusaka, C., and Kurihara, Y. (1975). Surveys of the fauna and flora in the water and soil of paddy fields. Reports of the Institute for Agricultural Research, Tohoku University No. 26. pp. 25–35.
- Kurasawa, H. (1956). The weekly succession in the standing crop of plankton and zoobenthos in the paddy field [in Japanese]. *Shigen Kagaku Kenshyusho Iho* 45, 86–99.
- Kurihara, Y., and Kikuchi, E. (1988). The use of tubificids for weeding and aquaculture in paddy fields. *Journal for Tropical Ecology* 4, 1–9.
- Lim, R. P., and Wong, M. C. (1986). The effect of pesticides in the population dynamics and production of *Stenocypris major Baird (Ostracoda)* in ricefields. *Archives für Hydrobiologie* 106, 421–7.
- Mahapatra, R. N., and Rajaramamohan Rao, V. (1981). Influence of hexacyclohexane on the nitrogenase activity of rice rhizosphere soil. *Plant and Soil* 59, 473–8.

- Mitsui, S., Watanabe, I., Honma, M., and Honda, S. (1964). The effect of pesticides on the denitrification in paddy soil. *Soil Science and Plant Nutrition* **10**, 107-15.
- Mogi, M. (1987). Effect of changing agricultural practices on the transmission of Japanese encephalitis in Japan. In 'Effect of Agricultural Development on Vector-Borne Diseases.' pp. 93-100. (FAO: Rome.)
- Moon, Y. H., and Kuwatsuka, S. (1984). Properties and conditions of soils causing the dechlorination of the herbicide benthocarb in flooded soil. *Journal of Pesticide Science* **9**, 745-54.
- Muirhead, W. A., De Datta, S. K., Roger, P. A., and Gusto, R. M. (1990). Effect of algicides in reducing NH_3 loss from urea applied to transplanted rice. I. Floodwater chemistry and biota. *Fertilizer Research* **21**, 95-100.
- Nakamura, Y., Ishikawa, K., Kuwatsuka, S. (1977). Degradation of benthocarb in soils as affected by soil conditions. *Journal of Pesticide Science* **2**, 7-16.
- Nayak, D. N., and Rajarammohan Rao, V. (1980). Pesticides and heterotrophic nitrogen fixation in paddy soils. *Soil Biology and Biochemistry* **12**, 1-4.
- Nishio, M. (1984). Some new soil-microbiological problems accompanying with the recent changes of agricultural systems in Japan. Bulletin of the Institute for Agricultural Research of Tohoku University No. 36 pp. 67-75. [in Japanese, English summary].
- Nishio, M., and Kusano, S. (1978). Effects of long-term application of organophosphate insecticides on bacterial numbers and nitrification in soil. *Journal of the Central Agricultural Experimental Station* **28**, 39-48. [in Japanese, English summary].
- Noble, J. C., and Happey-Wood, C. M. (1987). Some aspects of the ecology of algal communities in ricefields and rice irrigation systems of southern New South Wales. *Journal of the Australian Institute of Agricultural Sciences* **53**, 170-84.
- Oka, I. N. (1988). Future needs for pesticide management in southeast Asia. In 'Pesticide Management and Integrated Pest Management in Southeast Asia.' (Eds P. S. Teng and K. L. Heong.) pp. 1-11. Consortium for International Crop Protection, USAID, MD, USA.
- Rao, J. L. N., Pasalu, I. C., Rajarammohan Rao, V. (1983). Nitrogen fixation (C_2H_2 reduction) in the rice rhizosphere soil as influenced by pesticides and method of their application. *Journal of Agricultural Science* **110**, 673-42.
- Read, D. C. (1987). Greatly accelerated microbial degradation of aldicarb in re-treated field soil, in flooded soil, and in water. *Journal of Economic Entomology* **80**, 156-63.
- Roger, P. A., and Bhuiyan, S. I. (1990). Ricefield ecosystem management and its impact on disease vectors. *Water Resources Development* **6**, 2-18.
- Roger, P. A., Heong, K. L., and Teng, P. S. (1991). Biodiversity and sustainability of wetland rice production: role and potential of microorganisms and invertebrates. In 'The Biodiversity of Microorganisms and Invertebrates: its Role in Sustainable Agriculture.' (Ed. D. L. Hawksworth.) pp. 117-36. (CAB International: Wallingford, UK.)
- Roger, P. A., Kulasooriya, S. A., Barraquio, W. L., and Watanabe, I. (1981). Epiphytic nitrogen fixation on lowland rice plants. In 'Nitrogen Cycling in Southeast Asian Wet Monsoonal Ecosystems.' (Eds R. Wetselaar, J. R. Simpson and T. Roswall.) pp. 62-6. (The Australian Academy of Science: Canberra.)
- Roger, P. A., and Kurihara, Y. (1991). Floodwater biology of tropical wetland ricefields. In 'Soil Management for Sustainable Rice Production in the Tropics.' (Eds S. Panichapong and H. Wada.) International Board for Soil Research and Management. Monograph No. 2. pp. 211-33.
- Roger, P. A., Simpson I., Oficial R., Ardales S., and Jimenez, R. (1994). Impact of pesticides on soil and water microflora and fauna in wetland ricefields. In 'Rice Pest Science and Management'. Selected papers from the International Rice Research Conference. (Eds P. S. Teng, K. L. Heong and K. Moody.) pp. 255-76. (IRRI: PO Box 933, Manila.)
- Roger, P. A., Zimmerman, W. J., and Lumpkin, T. (1993). Microbiological management of wetland rice fields. In 'Soil Microbial Technologies.' (Ed. B. Metting.) pp. 417-55. (Marcel Dekker: New York.)
- Sato, R., and Kubo, H. (1964). The water pollution caused by organophosphorus insecticides in Japan. *Advances in Water Pollution Research* **1**, 95-9.
- Sethunathan, N. (1972). Diazinon degradation in submerged soil and rice-paddy water. *Advances in Chemistry Series* **111**, 244-55.
- Siddaramappa, R., and Watanabe, I. (1979). Evidence for vapor loss of ^{14}C -carbofuran from rice plants. *Bulletin of Environmental Contamination and Toxicology* **23**, 544-51.
- Simpson, I. C., Roger, P. A., Oficial, R., and Grant, I. F. (1993a). Impacts of agricultural practices in aquatic oligochaete populations in ricefields. *Biology and Fertility of Soils* **16**, 27-33.
- Simpson, I. C., Roger, P. A., Oficial, R., and Grant, I. F. (1993b). Density and composition of aquatic oligochaete populations in different farmers' ricefields. *Biology and Fertility of Soils* **16**, 34-40.
- Simpson, I. C., Roger, P. A., Oficial, R., and Grant, I. F. (1994a). Effects of fertilizer and pesticide management on floodwater ecology in wetland ricefield: I. Experimental design and dynamics of the photosynthetic aquatic biomass. *Biology and Fertility of Soils* **17**, 129-37.
- Simpson, I. C., Roger, P. A., Oficial, R., and Grant, I. F. (1994b). Effects of fertilizer and pesticide management on floodwater ecology in wetland ricefield: II. Dynamics of microcrustacean and dipteran larvae. *Biology and Fertility of Soils* **17**, 138-46.
- Simpson, I. C., Roger, P. A., Oficial, R., and Grant, I. F. (1994c). Effects of fertilizer and pesticide management on floodwater ecology in wetland ricefield: III. Dynamics of benthic molluscs. *Biology and Fertility of Soils* **18**, 219-27.
- Smith, R. J., Flinchum, W. T., and Seaman, D. E. (1977). Weed control in US rice production. Agricultural Handbook No. 497. (USDA: Washington DC.)
- Takamura, K., and Yasuno, M. (1986). Effects of pesticide application on chironomid larvae and ostracods in ricefields. *Applied Entomology and Zoology* **21**, 370-6.
- Tomaselli, L., Giovannetti, L., and Materassi, R. (1987). Effect of simazine on nitrogen-fixing cyanobacteria in soil. *Annali di Microbiologia ed Enzimologia* **37**, 183-92.
- Vlek, P. L. G., Stumpe, J. M., and Byrnes, B. M. (1980). Urease activity and inhibition in flooded soil system. *Fertilizer Research* **1**, 191-202.
- Wainright, M. (1978). A review of the effects of pesticides on microbial activity in soils. *Journal of Soil Science* **29**, 287-98.
- Watanabe, I. (1977). Pentachlorophenol-decomposing and PCP-tolerant bacteria in field soil treated with PCP. *Soil Biology and Biochemistry* **9**, 99-103.

- Watanabe, I. (1978). Pentachlorophenol (PCP) decomposing activity of field soils treated annually with PCP. *Soil Biology and Biochemistry* **10**, 71-5.
- Watanabe, I., and Inubushi, K. (1986). Dynamics of available nitrogen in paddy soils. I. Changes in available N during rice cultivation and origin of N. *Soil Science and Plant Nutrition* **32**, 37-50.
- Watanabe, I., De Datta, S. K., and Roger, P. A. (1988). Nitrogen cycling in wetland rice soils. In 'Advances in Nitrogen Cycling in Agricultural Ecosystems.' (Ed. J. R. Wilson.) pp. 239-56. (CABI International: Wallingford, UK.)
- Yasumatsu, K., Hashimoto, H., and Chang, Y. D. (1979). Chironomid fauna of Korea and their role in the rice agroecosystem. *International Rice Research Newsletter* **4**, 17-18.
- Yoshida, T., and Castro, T. F. (1970). Degradation of gamma-BHC in rice soils. *Soil Science Society of America Proceedings* **34**, 440-2.
- Yu-Lin Chen (1980). Degradation of butachlor in paddy fields. In 'Weeds and Weed Control in Asia.' pp. 121-41. (Food and Fertilizer Technology Center: Taiwan.)

Received 14 February 1994, accepted 2 August 1994