Biol Fertil Soils (1993) 16:27–33

Biology and Fertility of Soils

Impacts of agricultural practices on aquatic oligochaete populations in ricefields

Ian C. Simpson[1], Pierre A. Roger[2], Roberto Oficial[3], and Ian F. Grant[1]

[1] Natural Resources Institute, Central Avenue, Chatham Maritime, Kent ME4 4TB, UK
[2] Institut Français de Recherche Scientifique pour le Developpement en Cooperation, 213, rue la Fayette, F-75480 Paris Cedex 10, France
[3] International Rice Research Institute, P.O. Box 933, Manila, Philippines

Received: April 3, 1992

Summary. The impacts of N fertilizer, pesticides and green manure on aquatic oligochaetes in irrigated ricefields were investigated in experimental plots. Populations, determined by the wet sieving of soil cores, were dominated by the Tubificidae *Limnodrilus hoffmeisteri*. Total densities ranged from 0 to 40000 m^{-2}. Oligochaete numbers increased in response to additions of urea N. An inhibitory effect of carbofuran on oligochaete populations was observed during the first season of experimental pesticide treatments, but not during the following year. The green manure *Sesbania rostrata* stimulated population development more than *Azolla microphylla*. Populations in plots maintained as wet fallow remained low throughout the crop cycle. Population dynamics were associated with the crop cycle. Peak densities were achieved 30–50 days after transplanting.

Key words: Aquatic oligochaetes – Tubificidae – Ricefields – Pesticides – Fertilizer – Wet sieving method – *Sesbania rostrata* – *Azolla microphylla*

The native fertility of flooded ricefields depends on replenishment of soil nutrients. They are recycled from crop residues, rhizosphere exudates, and the photosynthetic aquatic biomass, and enter the system in rainfall and irrigation water. Nutrients available to the crop are mineralized by the soil microbial biomass and translocated to the rhizosphere. Aquatic invertebrates perform important roles in organic matter decomposition and nutrient translocation and are considered key components of ricefield fertility (Roger et al. 1987).

Aquatic oligochaete worms are known to be a major component of the invertebrate fauna of flooded rice soils but have been afforded little attention. Published papers refer almost exclusively to laboratory and microplot experiments (Roger and Kurihara 1988; Kurihara 1989). These experiments have shown that aquatic oligochaetes affect physical, chemical, and microbiological properties of soil; nutritional status of floodwater and its flora and fauna; and uptake of N by rice plants (Grant and Seegers 1985). Their influence is exerted through respiration, burrowing, ingestion, digestion, and excretion.

The introduction of early-maturing high-yielding rice varieties has taxed the soil heavily for nutrients, particularly N. Mineral and organic fertilizers have been applied to supplement nutrient availability and chemical pesticides have been used to control insects, weeds, and diseases. Impacts of the high-input rice production systems on aquatic oligochaetes and the possible consequences for long-term soil fertility are largely undocumented.

The absence of aquatic oligochaetes from some ricefields in Japan was attributed to the use of the herbicide pentachlorophenol (PCP). Populations reappeared when PCP was replaced with chloro nitrofen (CNP), nitrofen (NIP), and benthiocarb (Kurihara and Kikuchi 1988). Application of the insecticide endosulphan to a ricefield in Indonesia did not cause tubificid mortality (Gorbach et al. 1971). Earthworm populations in ricefields were adversely affected by carbofuran in Texas (Flickinger at al. 1980) and malathion in India (Senapati et al. 1991). Aquatic oligochaete population densities increased in Japanese ricefields after organic matter was incorporated (Kurihara and Kikuchi 1988). Kurihara (1989) reported that tubificid population densities were usually low where mineral N was applied.

The objective of the present study was to investigate the demography and ecology of aquatic oligochaete populations in ricefields and the impacts of agricultural practices typical of intensified irrigated rice production in Asia. This was achieved by an intensive investigation in experimental plots and extensive surveys in farmers' fields (Simpson et al. 1993). The specific objective of the experimental work was to assess the impacts of N fertilizer (deep-placed and broadcast), pesticides (carbofuran and butachlor), and green manures (*A. microphylla* and *S. rostrata*) on aquatic oligochaete populations.

Correspondence to: I. C. Simpson

Materials and methods

The experiment was conducted in a block of 65 plots (4×4 m) at the International Rice Research Institute (IRRI), Philippines. Fieldwork was conducted during the dry and wet seasons of 1989 (April–September) and during the dry seasons of 1990 (January–June) and 1991 (January–May). The experimental site was established in 1986 to investigate the impact of agricultural practices on various aspects of ricefield ecology. The experimental design consisted of 13 treatments (Table 1), with five replicates in randomized blocks. Although not all treatments were sampled during this investigation, they were maintained for other measurements.

Each plot contained a 1-m^2 microplot (metal frame pushed into the soil) from which light was excluded by a polystyrene cover. Sixteen 10-cm diameter holes were cut in each cover to accommodate rice plants (planted plots only). The soil was a Maahas silty clay loam (Aquic Tropudalf, pH 7.2, 0.18% N; Grant et al. 1983). Rice seedlings (IR72) were transplanted at 25- by 25-cm spacings. Plots and microplots were irrigated independently by a network of channels. Floodwater was maintained between 5 and 10 cm during the crop season, then drained 2 weeks before harvest, and the plots were reflooded during fallow periods.

All planted plots received 30 kg P ha^{-1} as triple superphosphate 6–7 days after transplanting. Prilled urea was broadcast in split applications, two-thirds 7 days after transplanting and one-third 55–61 days after transplanting. Deep-placed N was applied 6–7 days after transplanting as 3 g urea super granules 10 cm below the soil surface. They were positioned centrally between every second set of four adjacent rice hills.

S. rostrata and *A. microphylla* were used as green manure. *Sesbania* sp. seeds were broadcast 45 days before transplanting at 45 kg ha^{-1}. The plants were cut down, chopped up, and incorporated 2 weeks before transplanting. In 1990, *Azolla* sp. was inoculated at 0.4 kg m^{-2} 21 days before transplanting. P was applied three times at 2 kg P ha^{-1} (5-day intervals) to boost growth. The *Azolla* sp. was incorporated 7 days before transplanting. In 1991, *Azolla* sp. was grown outside the experimental area and incorporated 1 day before transplanting at 2 kg fresh weight m^{-2}.

In the 1990 dry season pesticide application was introduced as a treatment. Carbofuran was applied as 3% granules, a common practice, to permit accurate dosing and minimize cross-plot contamination. In the 1990 dry season three dosage rates were applied at three frequencies (Table 1). When insect infestations were observed, despite carbofuran application, brodan was applied at 0.1 or 0.2 kg a.i. ha^{-1}. In plots with higher pesticide doses (D, E, F, I, J, K, and L) the herbicide butachlor was applied at 0.35 kg a.i. ha^{-1} 3 days after transplanting. The pesticide treatments were modified for the 1990 wet season and the 1991 dry season (Table 1). Butachlor was applied only in plots receiving the highest carbofuran doses (B, E, I, and L) at 0 days after transplanting. No brodan was applied. The schedule of agrochemical applications during the 1990 and 1991 dry seasons are shown in Tables 2 and 3. Chemical descriptions of pesticides are given in the Appendix. Pesticide dosage rates were chosen to represent the range of application levels found in a survey of 33 farms in the Laguna Province, Philippines, in 1989.

It was not possible to enumerate aquatic oligochaetes in all plots at regular intervals because of the large number of plots and the resulting high numbers of individual samples. Consequently, only specific combinations of treatments were studied each crop season. Samples were taken in all plots only at crop maturity in the dry season of 1989, at the end of the following fallow period, and at transplanting and crop maturity in the 1989 wet season. No-mineral-N (A), green-manure (G), and high-mineral-N (H) treatments were sampled at a higher frequency during the 1989 wet season. High-N treatments with different pesticide regimes (H, I, K, and L) were sampled during the 1990 dry season. Low and high N at three carbofuran levels (A, B, D, H, K, and L) and unplanted plots (M) were sampled during the 1991 dry season. Microplots were sampled during the 1989 dry and wet seasons.

To estimate the oligochaete populations 10 core samples (27 mm diameter) were taken, down to the plough depth (approximately 20 cm), along two L-shaped transects within each plot. Transect sampling was chosen in preference to a randomized method to avoid plot margins, reduce the sampling duration, and minimize soil disturbance. The transects were L-shaped to avoid the microplots positioned in a corner of each plot. Core samples from each transect were collected in separate plastic bags and processed as composite samples. Oligochaetes in the microplots were enumerated from four soil cores which were processed as composite samples.

Table 1. Experimental ricefield treatments from 1989 to 1991

	Fertilizer			Carbofuran		1990 WS Fertilizer	1991 DS Carbofuran	
	1989 DS	1989 WS	1990 DS	Q	F		Q	F
A	Zero	Zero	Zero	0.1	1*	Zero	0	0
B	S(55)	S(73)	S(55)	0.1	1*	Zero	0.5	5
C	DP(55)	DP(55)	DP(55)	0.1	1*	DP(55)	0	0*
D	Zero	Zero	Zero	0.3	2*	Zero	0.3	1
E	S(55)	S(73)	S(55)	0.3	2*	*Azolla* sp.	0.5	5*
F	DP(55)	DP(55)	DP(55)	0.3	2*	DP(55)	0.3	1*
G	Zero	*Sesbania* sp.	*Azolla* sp.	0.1	1*	*Azolla* sp.	0	0*
H	S(110)	S(147)	S(110)	0.1	1	S(110)	0	0
I	S(110)	S(147)	S(110)	0.3	5	DP(55)	0.5	5*
J	Zero	*Azolla* sp.	*Azolla* sp.	0.3	2*	*Azolla* sp.	0.3	1
K	S(110)	S(147)	S(110)	0.3	2	S(110)	0.3	1
L	S(110)	S(147)	S(110)	0.5	5	S(110)	0.5	5
M	Zero	Zero	Fallow	0	0*	Fallow	0	0

DS, Dry season; WS, wet season; S, split application (kg N ha^{-1}); DP, deep-placed (kg N ha^{-1}); Q, carbofuran quantity at each application (kg a.i. ha^{-1}); F, application frequency; 1990 wet season not sampled as part of this investigation; a.i., active ingredient

Table 2. Agrochemical applications in the experimental ricefields during the dry season crop 1990

DT	Treatment
3	Butachlor, treatments D, E, F, I, J, K, and L
7	N and P fertilizer
10	Brodan (0.1 kg a.i. ha^{-1})
13	Carbofuran, treatments D, E, F, I, J, K, and L
28	Carbofuran, treatments I and L
35	Brodan (0.1 kg a.i. ha^{-1})
42	Carbofuran, treatments I and L
54	Carbofuran, all plots
55	N fertilizer
69	Carbofuran: treatment I and L
73	Brodan (0.2 kg a.i. ha^{-1})

DT, Days after transplanting; a.i., active ingredient

Table 3. Agrochemical applications in the experimental ricefields during the dry season crop 1991

DT	Treatment
0	Butachlor, treatments B, E, I, and L
6	N and P fertilizer
14	Carbofuran, treatments B, E, I, and L
28	Carbofuran, treatments B, E, I, and L
45	P fertilizer
47	Carbofuran, treatments B, D, E, F, I, J, K, and L
54	Carbofuran, treatments B, E, I, and L
61	N fertilizer
70	Carbofuran, treatment B, E, I, and L

DT, Days after transplanting

The number of core samples required to obtain a satisfacory estimate of population density was determined by the method of Roger et al. (1991). Sixteen soil cores were collected randomly from a plot and the oligochaetes extracted. Coefficients of variation (CV) were determined for nine series of 112 density estimates, calculated by random selection of 2–10 subsamples among 16. The CV of 70% for 16 single-locus measurements declined rapidly when composite sampling was used and the number of subsamples increased. For a composite sample of 10 soil cores, the CV was 17%; this did not improve significantly by increasing the number of subsamples beyond 10. This accuracy was considered sufficient (<20%) for measurements at the plot level, because of the very high variability expected among replicates.

About 200 ml water was added to each sample, which was then gently squeezed to break up the core structure. This procedure reduced the amount of washing required to extract the aquatic oligochaetes, the time required to process each sample, and the possibility of damage to the organisms. The samples were transferred into a series of graded sieves with mesh sizes of 2, 1, and 0.25 mm. The finest mesh used was suitable for the retention of small Tubificidae (Stimpson et al. 1982) and Naididae (Hiltunen and Klemm 1980). Soil retained on the mesh was washed away with a fine jet of water until the percolating water was clear.

Material retained on each mesh was backwashed into sorting trays. The aquatic oligochaetes were located visually, removed with either a fine pair of forceps (large worms) or a Pasteur pipette (small worms), and counted. The samples were sorted live because movement greatly increased recovery efficiency (approximately 80%). The specimens obtained were anesthetized in 10% ethanol, fixed in 4% formaldehyde solution for 24 h, and stored in 80% ethanol (Lincoln and Gordon-Sheal 1979).

Population densities were expressed in numbers per square meter. Species compositions were determined for each population. Twenty per cent (down to a minimum of five or all individuals if less than five) of each sample was slide-mounted in polyvinyl lactophenol. Specimens were selected for mounting on the basis of dissimilarity under the binocular microscope. If all individuals mounted were of the same species they were considered to contribute 100% of the population; if different, a further cross-section of individuals was examined. The specimens were identified using the keys and descriptions by Brinkhurst (1963), Brinkhurst and Jamieson (1971), Hiltunen and Klemm (1980), and Stimpson et al. (1982).

Results

Aquatic oligochaete densities in individual plots ranged from 0 to 40000 m^{-2}. Populations in all treatments were dominated by the tubificid species *Limnodrilus hoffmeisteri* (Claparédé) (Table 4). Other species recorded included the Tubificidae *Branchiura sowerbyi* (Beddard) and *Aulodrilus piqueti* (Kowaleski), and the Naididae *Dero digitata* complex (Müller) and *Dero dorsalis* (Feronière). *Dero digitata* is referred to as a complex because some authors consider it a polymorphic species, while others believe it can be separated into three species.

The linear regression between the logarithm of means and variances of counts in replicated plots had a slope of 1.7, indicating a log-normal distribution. This was sufficiently close to 2 to permit analysis of variance to be performed on log-transformed data (X+1) (Roger et al. 1991). The significance of differences among treatments was tested on transformed data with Duncan's multiple range test.

When all treatments were considered as independent and when replicated treatments were combined, no significant differences were found among populations at crop maturity in the 1989 dry season or during the fallow period (Table 5). Absolute population densities were low at crop maturity before the plots were drained (1989 dry season) but increased during the wet fallow period (means 700 m^{-2} and 2600 m^{-2}, respectively).

At transplanting in the 1989 wet season crop, populations were not significantly different except in the *Sesbania* sp. treatments, where they were more dense (Table 6). Differences among treatments at crop maturity were highly significant. The oligochaete density responded positively to the quantity of N fertilizer broadcast. Largest populations were observed in plots where *Sesbania* sp. was grown and incorporated. No significant difference was found between the unplanted and no-N controls and the plots where *Azolla* sp. was incorporated or N fertilizer deep-placed (Table 6). Mean population densities increased from 3000 m^{-2} at transplanting to 6000 m^{-2} at crop maturity. Oligochaetes were virtually absent from the dark microplots (data not shown).

The dynamics of oligochaete populations in the 1989 wet seasons are illustrated in Fig. 1. At transplanting, populations were more dense in the treatment where *Sesbania* sp. had been incorporated. No difference was

Table 4. Oligochaete population composition for each treatment at crop maturity in the 1989 dry season (DS) and during the following fallow period (F)

N treatment (kg N h^{-1})	Number of individuals		Aquatic oligochaete species (%)									
			L.h.		*B.s.*		*D.di.*		*D.do*		*A.p.*	
	DS	F	DS	F	DS	F	DS	F	DS	F	DS	F
Zero	54	358	90	75	4	6	2	9	2	10	2	–
55 b/cast	35	117	100	86	–	4	–	5	–	5	–	–
55 USG	46	130	100	100	–	–	–	–	–	–	–	–
110 b/cast	128	350	96	88	4	7	–	5	–	–	–	–

Number of individuals, Number from which species compositions were determined; b/cast, broadcast urea in two splits; USG, Urea super granules deep-placed; *L.h., Limnodrilus hoffmeisteri; B.s., Branchiura sowerbyi; D.di., Dero digitata; D.do., Dero dorsalis; A.p., Aulodrilus piqueti.* Treatments combined: Zero N (A, D, G, J, and M); 55 kg N ha^{-1} broadcast (B and E); 55 kg N ha^{-1} deep-placed (C and F); and 110 kg N ha^{-1} broadcast (H, I, K, and L)

Table 5. Summary of aquatic oligochaete populations (no. m^{-2}) at crop maturity in the 1989 dry season and during the following fallow period

Treatment	n	Oligochaete population densities	
		Crop maturity	Fallow
ANOVA P values		0.71	0.52
0 N	20	370	2650
55 kg N ha^{-1}	10	610	2040
55 kg N ha^{-1} DP	10	800	2270
110 kg N ha^{-1}	20	1120	3060
0 N, 0 P	5	420	1920

n, Number of plots per treatment; ANOVA, analysis of variance; DP, deep-placed fertilizer found between the zero-N and high-N treatments, before fertilizer application. All populations had increased to similar maxima (12000 m^{-2}) by 30 days after transplanting. Dramatic crashes were observed in all populations before 49 days after transplanting. They recovered in the *Sesbania* sp. and high-N treatments, but remained significantly lower in the control.

The dynamics of oligochaete populations receiving different pesticide treatments are shown in Fig. 2 (1990 dry season). Before transplanting, populations were similar in all treatments. In treatments which received carbofuran and butachlor before 20 days after planting population densities remained similar. In the treatment which did not receive pesticide applications, populations increased significantly (Fig. 2). By 50 days after transplanting all populations had increased. However, the population in the lowest pesticide treatment was still significantly higher. Towards the end of the crop cycle all populations declined, but lower pesticide inputs still corresponded with higher oligochaete densities.

Table 6. Summary of aquatic oligochaete populations (no. m^{-2}) at transplanting and crop maturity in the 1989 wet season

Treatment	n	Oligochaete population densities	
		Transplanting	Crop maturity
ANOVA *P* values		0.06	<0.01
0 N	10	1580	3410 a
73 kg N ha^{-1}	10	2420	6020 bc
55 kg N ha^{-1} DP	10	3050	4060 ab
147 kg N ha^{-1}	20	3080	8020 c
A. micorphylla	5	2140	2630 a
S. rostrata	5	6300	9240 c
Unplanted	5	2240	3750 ab

n, Number of replicate plots; ANOVA, analysis of variance; DP, deep-placed fertilizer; *A., Azolla; S., Sesbania*. Values followed by the same alphabetical letter are not significantly different ($P = 0.05$) by Duncan's multiple range test

Table 7. Summary of aquatic oligochaete population densities (no. m^{-2}) during the 1991 dry season including the results of one-way analysis of variance (ANOVA) on log-transformed data

	Oligochaete population densities					
	−3 DT	18 DT	39 DT	60 DT	81 DT	Mean
ANOVA *P* values	0.23	<0.01	0.01	<0.01	<0.01	<0.01
No, N						
No pesticide	64	36 a	64 ab	28 a	30 ab	45 a
Low pesticide	146	91 c	63 ab	58 b	54 bc	82 b
High pesticide	91	75 bc	78 b	84 b	116 d	89 b
110 kg N ha^{-1}						
No pesticide	66	69 bc	97 b	58 b	71 bcd	72 b
Low pesticide	95	68 bc	89 b	75 b	79 cd	81 b
High pesticide	110	123 c	101 b	72 b	112 d	104 b
Unplanted	49	38 ab	40 a	28 a	23 a	36 a

Population densities × 10^2 = means of five replicates; DT, days after transplanting, for other explanations, see footnotes to Table 6

Table 8. Summary of aquatic oligochaete population densities (no. $m^{-2} \times 100$) during the 1991 dry season, including the results of two-way analysis of variance (ANOVA) on log-transformed data

	Oligochaete population densities						
	n	−3 DT	18 DT	39 DT	60 DT	81 DT	Mean
ANOVA *P* values		0.79	0.11	0.03	0.04	0.07	0.10
No N	15	90	67	68 a	57 a	67	72
110 kg N ha^{-1}	15	100	86	96 b	69 b	88	86
ANOVA *P* values		0.10	<0.01	0.99	0.01	<0.01	0.01
No pesticide	10	65	53	80	43 a	51	58
Low pesticide	10	128	107	82	65 b	83	93
High pesticide	10	93	71	83	79 b	97	85
Interaction *P* values		0.93	0.16	0.32	0.20	0.03	0.23

DT, Days after transplanting; for other explanations, see footnotes to Table 6

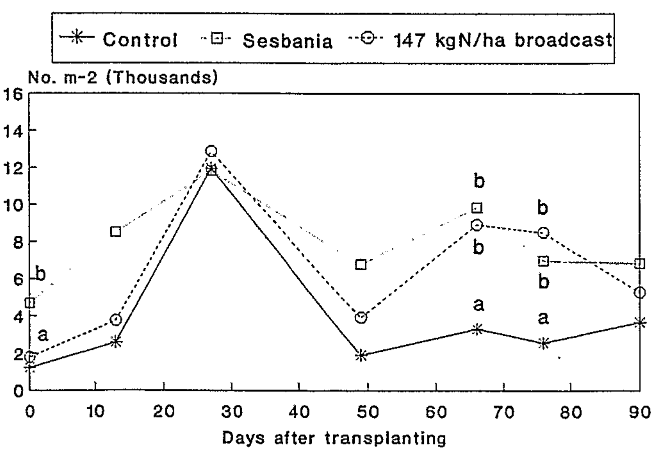

Fig. 1. Aquatic oligochaete population dynamics in the experimental ricefields during the 1989 dry season. Significant differences calculated using log-transformed data are indicated by different *alphabetical letters*

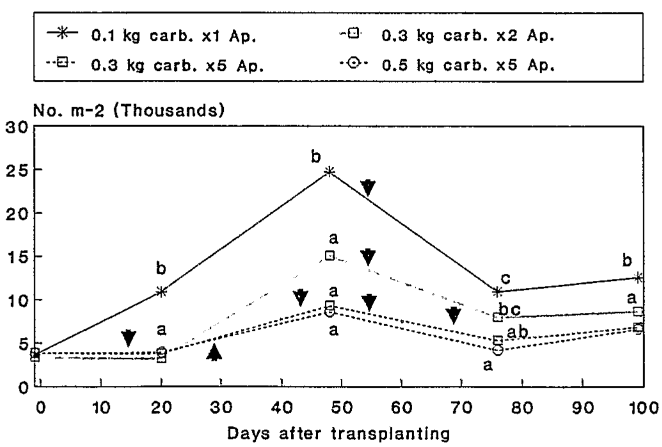

Fig. 2. Aquatic oligochaete population dynamics in the experimental ricefields during the 1990 dry season. Significant differences calculated using log-transformed data are indicated by different *alphabetical letters*. Applications (*Ap.*) of carbofuran are indicated by *arrows*

Results of the 1991 dry season experiment were initially analysed by one-way analysis of variance using treatments as the discriminatory factor (Table 7). The wet fallow plots yielded consistently low oligochaete numbers throughout the crop cycle, but they were not significantly different from the zero-N and no-pesticide treatment. Populations in other treatments were more dense and in most cases not significantly different from each other.

Two-way analysis of variance was performed on the data using two levels of N and three levels of pesticide (Table 8); the wet fallow treatment was removed from the analysis. Application of mineral N significantly increased the mid-crop population density. However, seasonal means were not significantly different. At the start of the crop season oligochaetes were significantly more numerous in the low-pesticide than the no-pesticide treatments. Carbofuran was not applied to the low-pesticide treatment until 47 days after transplanting, i.e., after the differences above were observed. By 39 days after transplanting populations at all pesticide levels were similar. Before the next sampling date the low- and high-pesticide treatments received applications. Thereafter, oligochaete population densities were significantly higher in the presence of pesticides.

At 81 days after transplanting, after all pesticide and fertilizer applications had been made, there was a significant interaction between pesticide and N (Table 8). The results of the one-way analysis of variance (Table 7) were examined for evidence of this interaction. Oligochaete populations were significantly denser at the high pesticide level only in the absence of mineral-N applications.

The dynamic trends observed in previous seasons were not evident in the 1991 dry season. Populations tended to be more stable, fluctuating only slightly between successive samplings.

Discussion

The dominance of the tubificids *Limnodrilus* sp. and *B. sowerbyi* has been reported in flooded rice soils (Kikuchi et al. 1977; Grant and Seegers 1985). Both are comparatively large and more easily recovered from samples than smaller species (e.g., naidids); this may introduce bias in the results.

The stimulatory effect of mineral N on aquatic oligochaete populations in the 1989 wet season and the 1991 dry seasons contrasts with the observations of Kurihara (1989). The relationship was probably mediated through the photosynthetic aquatic biomass. Enhanced N availability promotes the growth of photosynthetic aquatic biomass, potentially increasing the oligochaetes' food supply (organic matter and associated microorganisms) and raising the ecosystem's carrying capacity. The importance of the photosynthetic aquatic biomass as a food supply was supported by the dearth of oligochaetes in light-excluded microplots; however, this could also be attributed to other factors associated with enclosing the system.

The evidence of pesticide impacts on the aquatic oligochaete populations was inconsistent. Oligochaete densities were adversely affected by pesticide applications in the 1990 dry season experiment, but there was evidence in the 1991 dry season that populations were stimulated. It is difficult to a find a satisfactory explanation to account for the differences between the two seasons.

Adverse effects of carbofuran on aquatic oligochaete populations in the 1990 dry season were not expressed as density reductions: rather, populations were inhibited from further development relative to treatments that did not receive pesticide. There are several possible reasons for this effect, including interference with reproduction, maturation, and behaviour.

Perhaps carbofuran concentrations were insufficient to cause adult mortality but immature worms and cocoons were susceptible, thus reducing recruitment to the adult population. Immature individuals of the earthworm species *Darwida willsi* were observed to be more susceptible to malathion stress than adults in Indian ricefields (Senapati et al. 1991).

Oligochaetes exposed to pesticides at sublethal doses have displayed hyperactivity, muscular contractions, blood clotting, and altered burrowing activity (Whitten and Goodnight 1966; Naqvi 1973; Chapman et al. 1982; Keilty et al. 1988 a, b). Perhaps changes in their behavior patterns are sufficient to interfere with their reproductive potential.

In the 1991 dry season there was some evidence that aquatic oligochaete densities were higher where carbofuran was applied. Positive effects of some pesticides have been reported on earthworm populations in cultivated aerobic soils (Senapati et al. 1991). However, this does not explain why the populations in the present study responded negatively one year and positively the next.

The apparent stimulatory effects of carbofuran in the 1991 dry season could be explained by the combined effects of antecedent conditions, the oligochaete life-cycle, and adaptation. Populations in the pesticide-treated plots were depressed the previous year. If resources were underused, populations could have developed to exploit them during the wet fallow period. Oligochaete density reductions caused by carbofuran in the 1990 dry season were probably not a consequence of adult mortality. Therefore, established adult populations may not decline after pesticide applications, but could be prevented from further increases, as was observed. Keilty and Landrum (1990) reported that populations of aquatic oligochaetes were capable of adapting to stressful chemical conditions.

Many aquatic oligochaetes, including *Limnodrilus* spp. and *B. sowerbyi,* are known to be tolerant of a wide range of pesticides (Whitten and Goodnight 1966; Naqvi 1973; Bailey and Lui 1980), particularly in the presence of sediment (Chapman et al. 1982) and in polyculture (Chapman and Brinkhurst 1984; Keilty et al. 1988 c). Explanations for the tolerance of oligochaetes to pesticides have been suggested by Whitten and Goodnight (1966) and Naqvi (1973). The absence of aquatic oligochaete mortality after pesticide applications in ricefields is supported by the work of Gorbach et al. (1971).

Aquatic oligochaetes were significantly more abundant at transplanting and at crop-maturity in the 1989 wet season crop in plots where *Sesbania* sp. was grown and incorporated, than in controls or where *Azolla* sp. was incorporated. Why population densities of aquatic oligochaetes should increase in the *Sesbania* sp. treatment and not in the *Azolla* sp. treatment is unclear. Perhaps the organic matter of the *Azolla* sp. is less suitable as a substrate for oligochaetes or maybe *Azolla* sp. decomposition products are directly or indirectly harmful.

Antecedent fallow conditions should be considered when interpreting the results of the following crop season. During this period in the present study oligochaete population densities equilibrated among treatments. Absolute density relative to that at the end of the previous crop will depend on hydrological conditions of the fallow period. If flooded conditions are maintained, populations can increase, aided by greater organic matter availability in the form of crop residues remaining after harvest. If the soil dries out populations will be significantly reduced. Antecedent fallow conditions and possibly intermittent drying could explain the relatively low oligochaete densities at the end of the 1989 dry season in the present study. Population increases in later seasons were permitted to develop by maintaining wet fallow conditions and paying more attention to floodwater management during the crop.

Although the treatments sampled were different each season, crop dynamics were similar. Oligochaete population densities in the 1989 wet season and 1990 dry season increased to peaks between 30 and 50 days after transplanting and declined towards the end of the season, except in the high-pesticide treatment 1990 wet season. Similar patterns have been observed previously in IRRI ricefields (Grant et al. 1993). Floodwater primary productivity is controlled by seasonal changes in nutrient and light availability, and perhaps oligochaete population dynamics reflect these changes.

The importance of aquatic oligochaetes in nutrient recycling and translocation is related to their density and activity rates. Population dynamics are connected with crop development and modified by management strategies. Therefore agricultural practices that interfere with population development and cause behavioral changes may affect long-term soil fertility.

Conclusions

(1) Aquatic oligochaete populations were dominated by the tubificid species *Limnodrilus hoffmeisteri* (1989).
(2) The insecticide carbofuran interfered with population densities and dynamics (1990 and 1991 dry seasons).
(3) Population densities were higher in plots where N fertilizer was broadcast (1989 wet season and 1991 dry season).
(4) Incorporation of *S. rostrata* appeared to stimulate oligochaete population development (1989 wet season).
(5) Populations in fallow plots remained low throughout the crop cycle (1991 dry season).
(6) Crop development controlled population dynamics, peak densities of $6000-25000\,m^{-2}$ were achieved 30–50 day days after transplanting (1989 wet season and 1990 dry season).
(7) Aquatic oligochaetes were virtually absent when photosynthetic aquatic biomass production was prevented (1989 dry and wet seasons).

Appendix: Pesticide descriptions

Benthiocarb: thiobencarb, S-4-chlorobenzyl diethyl (thiocarbamate); Brodan: 2/3 chlorpyrifos, 0,0-diethyl 0-3,5,6-trichloro-2-pyridyl phosphorothioate; 1/3 fenobucarb, 2-*sec*-butylphenyl methylcarbamate; butachlor: Machete, N-butoxymethyl-2-chloro-2′,6′-diethyl acetanilide); carbofuran: Furadan, 2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate; CNP: chloro nitrofen, 2,4,6-trichloro-1-(4-nitrophenoxy) benzene; endosulphan: (1,4,5,6,7,7-hexachloro-8-9-10-trinorborn-5-en-2,3-ylene) (dimethyl sulphite); malathion: *S*-1,2-bis(ethoxycarbonyl)ethyl *O,O*-dimethyl phosphorodithioate; NIP: nitrofen, 2,4-dichlorophenyl 4-nitrophenyl ether; PCP: pentachlorophenol

Acknowledgments. This research was conducted under a scientific agreement between IRRI (Philippines), NRI (United Kingdom) and ORSTOM (France), and is incorporated in the PhD thesis of I. C. Simpson, University of Wales College of Cardiff.

References

Bailey HC, Lui DHW (1980) *Lumbriculus variegatus*, a benthic oligochaete, as a bioassay organism. In: Eaton JC, Parish PR, Hendricks AC (eds) Aquatic toxicology. ASTM STP 707, American Society for Testing and Materials, Philadelphia, pp 205–215

Brinkhurst RO (1963) A guide for the identification of British aquatic Oligochaeta. Freshwater Biol Assoc Sci Publ no. 22, Ambleside, Cumbria, UK

Brinkhurst RO, Jamieson BGM (1971) Aquatic oligochaetes of the world. Oliver and Boyd, Edinburgh

Chapman PM, Brinkhurst RO (1984) Lethal and sublethal tolerances of aquatic oligochaetes with reference to their use as a biotic index of pollution. Hydrobiologia 115:139–144

Chapman PM, Farrell MA, Brinkhurst RO (1982) Relative tolerances of selected aquatic oligochaetes to individual pollutants and environmental factors. Aquat Toxicol 2:47–67

Flickinger EL, King KK, Stout WF, Mohn MM (1980) Wildlife hazards from Furadan 3G applications to rice in Texas. J Wildl Manage 44:190–197

Gorbach S, Haaring R, Knauf W, Werner HJ (1971) Residue analysis in the water system of East-Java (River Brantas, Ponds, Sea-water) after continued large-scale applications of Thiodan in rice. Bull Environ Contam Toxicol 6:40–47

Grant IF, Seegers R (1985) Tubificid role in soil mineralisation and recovery of algal nitrogen by lowland rice. Soil Biol Biochem 17:559–563

Grant IF, Tirol AC, Aziz T, Watanabe I (1983) Regulation of invertebrate grazers as a means to enhance biomass and nitrogen fixation of Cyanophyceae in wetland rice fields. Soil Sci Soc Am J 47:669–675

Hiltunen JK, Klemm DJ (1980) A guide to Naididae (Annelida: Clitellata: Oligochaete) of North America. Environmental Protection Agency-600/4-80-031, Washington DC

Keilty TJ, Landrum PF (1990) Population-specific toxicity response by freshwater oligochaete, *Stylodrilus heringianus*, in natural Lake Michigan sediments. Environ Toxicol Chem 9:1147–1154

Keilty TJ, White DS, Landrum PF (1988a) Sublethal responses to endrin in segment by *Limnodrilus hoffmeisteri (Tubificidae)*, and in mixed culture with *Stylodrilus heringianus* (Lumbriculidae). Aquat Toxicol 13:227–250

Keilty TJ, White DS, Landrum PF (1988 b) Sublethal exposure to endrin in sediment by *Stylodrilus heringianus* (Lumbriculidae) as measured by a cesium marker layer technique. Aquat Toxicol 13:251–279

Keilty TJ, White DS, Landrum PF (1988 c) Short-term lethality and sediment avoidance assays with endrin contaminated sediment and two oligochaetes from Lake Michigan. Arch Environ Contam Toxicol 17:95–101

Kikuchi E, Furusaka C, Kurihara Y (1977) Effects of tubificids (*Branchiura sowerbyi* and *Limnodrilus socialis*) on the nature of a submerged soil ecosystem. Jpn J Ecol 27:163–170

Kurihara Y (1989) Ecology of some ricefields in Japan as exemplified by some benthic fauna, with notes on management. Int Rev Ges Hydrobiol 74:507–548

Kurihara Y, Kikuchi E (1988) The use of tubificids for weeding and aquaculture in paddy fields. J Trop Ecol 4:393–401

Lincoln RJ, Gordon-Sheal J (1979) Invertebrate animals, collection and preservation. British Museum (Natural History), London, pp 48–50

Naqvi SMZ (1973) Toxicity of twenty-three insecticides to a tubificid worm *Branchiura sowerbyi* from the Mississippi Delta. J Econ Entomal 66:70–74

Roger PA, Kurihara Y (1988) Floodwater biology of tropical wetland ricefields. In: Int Symp Paddy Soil Fertility. International Soil Science Society, The Hague, pp 275–300

Roger PA, Grant IF, Reddy PM, Watanabe I (1987) The photosynthetic aquatic biomass in wetland rice fields and its effect on nitrogen dynamics. Efficiency of nitrogen fertilizers for rice. International Rice Research Institute, Los Baños, Philippines, pp 43–68

Roger PA, Jimenez R, Santiago-Ardales S (1991) Methods for studying blue-green algae in ricefields: Distribution ecology, sampling strategies and estimation of abundance. Res Pap no. 150, International Rice Research Institute, Los Baños, Philippines

Senapati BK, Biswal J, Sahu SK, Pani SC (1991) Impact of malathion on *Darwida willsi* Michaelsen, a dominant earthworm in rice fields. Pedobiologia 35:117–128

Simpson IC, Roger PA, Official R, Grant IF (1992) Density and composition of aquatic oligochaete populations in different farmers' ricefields. Biol Fertil Soils 16:34–40

Stimpson KS, Klemm DJ, Hiltunen JK (1982) A guide to the freshwater Tubificidae (Annelida: Clitellata: Oligochaeta) of North America. Environmental Protection Agency-600/3-82-033, Washington DC

Whitten BK, Goodnight CJ (1966) Toxicity of some common insecticides to tubificids. J Water Pollut Control Fed 38:227–235