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Ricefield ecosystem management and its impact on disease vectors

P.A. Roger and S.I. Bhuiyan

Wetland rice culture and irrigation schemes in tropical and subtropical regions create ecological conditions favourable to the propagation of diseases whose vectors require an aquatic environment. The most important are malaria, schistosomiasis and Japanese encephalitis. This paper reviews (1) the major features of the ricefield as an ecosystem for vectors of selected diseases, (2) the effects of the factors of crop intensification on vectors, and (3) the possible methods of vector control through management of the ecosystem which includes water management, especially the alternate wetting and drying method, conservation of natural enemies, utilization of pesticides of plant origin, and biological control by predators and pathogens.

Rice is the most widely grown crop throughout the tropics. About two thirds of the 143 million ha of riceland in the world are used for wetland rice culture in which water from rainfall and irrigation sources is conserved in the field to maintain a shallow flooded condition for almost the entire duration of the crop.

Flooding has beneficial effects on rice cultivation: (1) bringing the soil pH near to neutrality; (2) increasing the availability of nutrients, especially P and Fe; (3) maintaining soil N; (4) stimulating N_2 fixation; (5) depressing soil-borne diseases; (6) supplying nutrients from irrigation water; (7) decreasing weed incidence, especially those of C4 type; and (8) preventing soil erosion (Watanabe, De Datta and Roger, 1988).

However, wetland rice culture and irrigation schemes in tropical and subtropical regions create ecological conditions favourable to the propagation of vector-borne diseases (see Table 1). The most important are malaria, schistosomiasis and Japanese encephalitis, whose vectors require an aquatic environment, permanently or at certain stages of their life cycle.

This paper reviews (1) the major features of the ricefield as an ecosystem for vectors of selected diseases, (2) the effects of the factors of crop intensification on vectors, and (3) the methods of vector control through ecosystem management.

The ricefield as an ecosystem for vectors

The flooded ricefield is usually a temporary aquatic environment subject to large variations of sunlight, temperature, pH, O_2 concentration and nutrient status. Furthermore, ploughing, transplanting and weeding operations disrupt the establishment of community stability. Cultivation disturbs the ecosystem development as a secondary succession, and thereby prevents it from reverting to a marshland community (Watanabe and Roger, 1985).

The artificial and temporary nature of the ricefield ecosystem makes it a relatively unattractive environment to study, as frequent disturbances and agrochemical inputs interrupt classical ecological observations of community structure and energetics, nutrient cycling and population succession (Grant,

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P.A. Roger is Soil Microbiologist with ORSTOM, France, and Visiting Scientist at the International Rice Research Institute (IRRI), PO Box 933, Manila, the Philippines. S.I. Bhuiyan is Head of the Water Management Department of the IRRI.

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Table 1. Major vector-borne diseases that may be related to rice cultivation.

Major agent groups	Disease	Agent	Major vectors	Comments
Protozoa	Malaria	*Plasmodium falciparum,* *Plasmodium vivax,* *Plasmodium malariae*	*Anopheles* spp	60 *Anopheles* spp are vectors, 35 are considered as primary vectors. Larval stages are aquatic may breed in standing water
Trematodes and cestodes	Schistosomiasis	*Schistosomia haematobium,* *Schistosomia mansoni* *Schistosomia japonicum*	*Bilinus* spp, *Biomphalaria* spp	Spread by aquatic and amphibious snails.
	Other diseases caused by trematodes			Transmitted by snails through undercooked freshwater animals.
Nematodes	Guinea-worm disease			Transmitted through defective water supplies by water-flea-type crustacean.
	Filariasis	*Wucheeria bancrofiti,* *Brugia malayi,* *Brugia timori*	*Culex quinquefasciatus,* *Anopheles* spp, *Aedes* spp, *Mansonia* spp	
Arboviruses	Japanese encephalitis		*Culex tritaeniorhynchus,* *Culex pseudovishnui,* *Culex vishnui,* *Culex annulus*	Viruses transmitted mainly by *Culex* spp, but also by *Aedes* spp, *Anopheles* spp and other mosquitoes breeding in irrigated fields.
	Dengue, other encephalitis and arbovirus infections			
Non-vector-borne diseases	Leptospirosis			Especially a problem of marshy land and irrigated agriculture.

Roger and Watanabe, 1986). As a result, ecological studies of the submerged soils of lowland ricefields are rare compared to those on freshwater lakes and rivers. Moroni (1961) conducted a pioneering ecological study in Italian ricefields. Heckman (1979) extensively studied a tropical ricefield in Thailand. A recent report by the Overseas Development Administration of the UK (ODA, 1984) provides extensive environmental and ecological data on a deepwater ricefield in Bangladesh.

Water environment

Water management. Proper water management of wetland ricefields takes into account the physiological requirements of the plants. Very shallow water or a fully saturated soil condition is recommended at the seedling stage. If seedlings are submerged the development of radicles is affected by a lack of oxygen. During the early vegetative growth phase shallow water facilitates tiller production and promotes root development. During the reproductive growth phase a large quantity of water is consumed. As rice is most sensitive to drought during the reproductive phase, a continuous flooded condition should be maintained during this period. During the ripening phase little water is needed, and fields are usually drained 10–15 days before the harvest to facilitate mechanical or manual harvesting (De Datta, 1981).

Depending on evapotranspiration, percolation and seepage rates, and the quantity of water used for land preparation, between 900 and 2500 mm of water can be used per cropping season. The average consumption in irrigated ricefields in 43 locations in seven rice-producing countries was 1240 mm per crop (Kung, 1971). According to De Datta (1981), whenever possible continuous flooding with 5–7.5 cm of water is best for optimum grain yield, nutrient supply and weed control.

In irrigated rice (which accounts for 53% of the world's rice area), the most important water management practices are (1) continuous static flooding, with a water depth varying from 2–3 cm to about 15 cm, (2) rotational irrigation, where the required amount of water is applied at regular intervals and the field may often be without standing water between irrigations but the soil does not dry out enough for stress to develop, and (3) continuous flowing irrigation in which a constant small water flow through the field is maintained (De Datta, 1981). The rotational irrigation method often requires the least water, and the flowing irrigation method the most.

In about half the rainfed lowland rice area (25% of the world's rice area) rainfall and water control are adequate to avoid major droughts or submergences detrimental to rice growth. The other half includes shallow areas, which can be drought- and/or submergence-prone, rainfed medium-deepwater and deepwater areas. There are about 9 million ha of low-lying ricelands on river deltas where 0.5 to more than 3 m water accumulates during the rainy season.

Water properties. Floodwater is a photic, aerobic environment in which aquatic communities of chemosynthetic and photosynthetic producers (bacteria, algae and aquatic weeds), invertebrate and vertebrate primary consumers (grazers), and secondary consumers (carnivorous insects and fish) provide organic matter to the soil and recycle nutrients.

The physical and chemical properties of floodwater exhibit marked variations during the day and during the crop cycle (Roger and Kurihara, 1988). Floodwater temperature depends mostly on air temperature, solar radiation, the density of the rice canopy and aquatic plants, the water depth and its dynamics. In the tropics maximum daily values may often reach 36–40 °C and go beyond 40 °C at the beginning of the crop. Daily variations range from a few °C to about 15 °C. They increase as water level decreases and are larger in temperate and subtropical areas than in tropical areas (Roger and Kurihara, 1988).

The concentration of O_2 in floodwater results from an equilibrium between production by the photosynthetic aquatic biomass, diffusion between air and water, and consumption by respiration and oxidation. As the partial pressures of CO_2 and O_2 are inversely proportional, O_2 concentration and pH are positively correlated. The daily O_2 concentration may vary from 2 to 20 ppm, while water pH may vary by more than 2 units. The largest daily changes are observed early in the crop when algal blooms develop after N fertilizer has been applied (Roger, 1987).

The chemical composition of floodwater depends on that of the irrigation water and the soil. Marked changes occur in response to dilution by rain, dispersion of the surface soil by cultivation practices and biological activities, and fertilizer application. Peaks of N and P usually decrease within 6–10 days following fertilizer application (Roger and Kurihara, 1988).

Mather and Trinh Ton That (1984) reported that both snails and mosquitoes can adapt to large variations in climatic variables, but seasonal and diurnal fluctuations do have a marked effect on such vector activities as feeding, breeding and the ability to transmit disease.

The rice plant

The rice plant affects the floodwater environment by the shade that it provides, which increases as the canopy enlarges. Under transplanted rice the light is reduced by 50% after 15 days, 85% after 30 days and 95% after 60 days (Kurasawa, 1956). The ensuing changes in light intensity affect the growth of photodependent organisms. Rice also indirectly affects the floodwater/soil communities by lowering the temperature and CO_2 concentrations under the canopy. Rice plants act as substrate for epiphytic growths (Roger *et al*, 1981) and provide mechanical support for many animal species. Pulmonate molluscs may escape high floodwater temperatures by resting on the stems at the air–floodwater interface. The time of rice canopy closure in relation to the time of flooding has major implications for vector multiplication (Garrity, 1988).

Photosynthetic aquatic biomass

The photosynthetic aquatic biomass that develops in the floodwater of wetland ricefields is composed of planktonic, filamentous and macrophytic algae, and vascular macrophytes which are primary producers, contributing significantly to the fertility of the ecosystem. Reported productivities of 0.5–1.0 g C/m^2/day correspond to 10–15% of the rice crop and are similar to the productivities reported in eutrophic lakes (Roger and Watanabe, 1984).

The presence or absence of aquatic plants is one of the ecological factors that determine the suitability of a habitat for mosquitoes and snails (Mather and Trinh Ton That, 1984). Aquatic plants provide shade, shelter, resting places and refuge from natural predators, and can also modify temperature and increase the oxygen concentration in water.

Fauna

After an extensive survey of the literature Fernando, Furtado and Lim (1979) concluded that ricefield aquatic fauna span the whole spectrum of freshwater fauna and may even include some brackish water species in river deltas, eg polychaetes and penaeid prawns. This high species diversity was attributed to a rapid recolonization of the ricefield by the fauna from contiguous water bodies after disturbances caused by cultivation activities or drying. The study by Heckman (1979) of a Thai ricefield for one year also indicated a wide faunal diversity with the record of 268 animal species. Rotifera (50 spp) and arthropoda (146 spp) were the most numerous taxa; 18 species of fish were also recorded. Recent studies show a decrease in species diversity under intensified cultivation (see below).

The ricefield fauna directly responsible for the breakdown of the photosynthetic biomass (primary production) consist of microcrustaceans and gastropods that feed on algae. These, together with the protozoans and rotifers, also recycle nutrients from decaying photosynthetic biomass. Translocation of primary production and its breakdown products from the surface to the deeper soil layers is expedited by tubificid worms. Secondary and tertiary consumers (carnivorous insects and fishes) also recycle nutrients in the ecosystem or cause an exportation of nutrients when collected for food by farmers (Roger and Kurihara, 1988).

Mosquitoes. The reproduction of mosquitoes in ricefields is affected by plant height, water depth, soil and other environmental conditions as well as cultural practices. Generally larval populations are low after transplanting, peak a few weeks later and then decline as the plants reach a height of 60–100 cm. This may be due to physical obstruction of oviposition, increased shade and the establishment of predators in the fields. Mosquito reproduction ceases when the fields are drained before harvest, or may continue at a low level in residual pools (Goonasekere and Amerashinge, 1988).

A succession of mosquito species has been observed in ricefields. Heliophilic species are prevalent during the early stages of rice growth but are gradually replaced by more shade-loving species with the increase in plant height and canopy development. In Burkina Faso, Carnevale and Robert (1987) observed that *Anopheles gambiae* developed from soil flooding to the booting stage of rice. From booting to heading, *A. pharoensis* was dominant; it was then replaced by *A. coustani* during the ripening phase.

Some sun-loving species are found mainly in water without vegetation, whereas many others prefer the presence of vegetation. For *Mansonia* vegetation is obligatory, because both larvae and pupae obtain their oxygen requirements by piercing submerged roots or stems. Wherever water lettuce (*Pistia*), water hyacinth (*Eichhornia*) or *Salvinia* are found, breeding by *Mansonia* should be suspected, although this species can also utilize other aquatic plants (Mather and Trinh Ton That, 1984).

Mosquito production in ricefields ranges from about 2/m^2/day for *Anopheles* (Hill and Cambournac, 1941) to about 20/m^2/day for *Culex tritaeniorhynchus* (Heathcote, 1970).

Gastropods. Aquatic snails are very common inhabitants of ricefields. They can develop large populations, especially in fields where organic manure is applied. Populations up to 1000/m^2 have been observed in Philippine ricefields (Grant, Roger and Watanabe, 1986). Some large species (*Pila* spp, *Pomacea* spp, *Ampullaria* spp) are collected as food. Some species, eg the golden apple snail (*Pomacea canaliculata*) might be detrimental to rice, grazing on young seedlings and azolla. A large golden apple snail can consume a blade of a rice seedling in 3–5 minutes and up to 15 g azolla in 12–24 hours (Saxena, de Laura and Justo, 1987). *Pomacea* snails have been recognized as an important rice pest in Taiwan, Japan and the Philippines. Of the 150 000 ha of ricefields infested with *P. canaliculata* in Taiwan, 90 000 were treated with molluscicides. Losses were estimated to be about US$31 million (Mochida, 1988).

Behaviour experiments showed that when snails had to choose between various soils, they were most often attracted (70–80%) to rice soils rather than to other soil types. The responsible agent was a water-soluble substance (Kurihara and Kadowaki, 1988).

Webbe (1988) reports that snails thrive in habitats devoid of higher plant life but with (1) rich microbial and microalgal flora, and/or (2) decaying plant material, which provide their principal food. Although they may not prefer any particular species of microflora, the quantitative composition of the diet is probably important in conditioning the habitat. *Oncomelania quadrasi* has been found to correlate positively with the presence of green algae but negatively with blue-green algae (BGA) (Webbe, 1988). Kurihara, Suzuki and Moriyama (1987) reported that *Cipangopaludina japonica* preferred unplanted muddy soil to rice-planted soil and had a productivity 4–5 times larger in unplanted plots, but no reason was found for this preference.

Feeding experiments on *C. japonica* (mud snail) with *Spirogyra* sp, a filamentous green alga very common in ricefields, showed that snails preferred to feed on bacteria developing on partly decomposed algae rather than on fresh algae. Snails mainly utilize proteins, but not high molecular weight carbohydrates (Kurihara and Kadowaki, 1988). The authors indicated algal excreta and BGA as sources of nutrients for snails.

Aquatic snails can multiply rapidly. *O. hupensis* spp can live up to 200 days, and other species reportedly live longer. *O. quadrasi* starts laying eggs by the age of 90–100 days or by the time it reaches 3.5 mm in size. A single copulation will enable a snail to lay eggs for several days. An average of two eggs are laid every five days. It was calculated that if only 16% of the eggs survived to maturity, each female adult snail could produce 4.4 adults in the next generation (Garcia, 1988).

Predators of vectors. Major vector predators are fish, and aquatic insect predators and their larvae. Numerous species of fish are inhabitants of the ricefield ecosystem and are traditionally collected as food. Ruddle (1982) has reviewed the rice-associated food-fish species. In the most primitive rice–fish culture systems, fish were concentrated in the lower portion of the ricefields and were given some protection from predation by placing cut branches in some deeper spots that were also used as fish reservoirs during the dry season (Heckman, 1979). In more advanced types of rice–fish culture a central canal is established in or near the field to protect fish from field drying and to allow easier harvesting; fingerlings are introduced at an appropriate time, artificial feeding is often done, and yields of a few hundred kg/ha can be obtained. Several reviews on rice–fish culture are available (eg Coche, 1967; ICLARM and SEARCA, 1986).

Ricefields contain a rich variety of insect predators of mosquito larvae (Service, 1977) such as back swimmers, gerrids, etc (*Hemiptera, Notonectidae*), dragonfly and damselfly nymphs (*Odonata*), and adult and larval predacious water beetles (*Coleoptera, Dytiscidae*). In Kenya about 30 species were confirmed to feed on mosquito larvae in the laboratory (Sugiyama, Tagaki and Maruyama, 1985; Watanabe *et al*, 1968). The most important species are of the family of *Odonata* (dragonfly and damselfly, nymphs), *Notonectidae* (back swimmer, nymphs and adults), *Dytiscidae* (predacious water beetle, adults and larvae), and three species of fish: *Orizias latipes, Carassius gibelie* and *Misgurmus fossils* (Mogi, 1988).

Predator fauna will vary considerably according to the rice cultivars grown, the height of the rice plant, and water management practices (Mather and Trinh Ton That, 1984).

Association of ricefields with vector-borne diseases

Numerous studies have shown the association of wetland rice culture with vector-borne diseases in various parts of the tropical world. But the relationships between rice culture and vector-borne diseases are complex and often highly site-specific. While almost all the important mosquito vectors that transmit Japanese encephalitis breed primarily in ricefields (Pant, 1979, cited by Gratz, 1988), those that transmit malaria or schistosomiasis do not.

In the case of malaria, one of the reasons for the complexity is that several anopheline mosquito species, which are the vectors of the disease, breed in ricefields but the environmental conditions suitable for breeding of various species differ within the overall ricefield ecosystem. Introduction of irrigated rice creates higher mosquito breeding surfaces, but at the same time the ecosystem undergoes significant changes that either favour or discourage the ecological niches required for the breeding of certain species. Such changes include the duration of flooding, water depth, water turbidity, temperature and shading pattern. These changes may shift the equilibrium of the mosquito population and species selection in the area, resulting in a decrease or increase in the transmission potential, depending on the species that find the changed ecosystem favourable or unfavourable for breeding.

Gratz (1988) has pointed out that it is difficult to determine how much of anopheline mosquito breeding actually takes place in ricefields in Asia, Africa and the Americas. Ricefields in the plains of Assam, India, were found free from the dangerous anophelines (Najera, 1988). Large ricefields in Malaya were found free of the local vector, *A. maculatus* (Muirhead-Thomson, 1951). In Burkina Faso malaria transmission was 2.5 times less intense in the rice-growing villages than in neighbouring villages (Carnevale and Robert, 1987). Bradley (1988) concluded that in Africa the role of ricefields in increasing malaria intensity is likely to be limited, but is important in prolonging the transmission season inasmuch as the larva of the key vector has seasonal extensive habitats outside the ricefields. A recent study by Sharma (1987) found that in India rice cultivation has a very weak relationship or none at all with malaria transmission. In large parts of the country where rice culture dominated, malaria was found to be negligible or extremely low. Najera (1988) concluded that, although ricefields still produce the highest densities of anophelines, rice growing today is not associated with the most serious malaria problem areas of the world.

Many studies have indicated that the development of irrigation systems in Africa, mostly for rice culture, has increased schistosomiasis transmission. Webbe (1988) cited examples of such a development for Egypt, the Sudan and Ghana. He also mentioned that in Mali high levels of schistosomiasis are associated with rice cultivation in the floodplains of the Niger river.

The association of Asian schistosomiasis with rice culture has also been reported by different authors. They found, however, that it is the irrigation and drainage ditches, rather than the ricefields *per se*, that are the major breeding grounds of the schistosome snails. Garcia (1988) relates these contrasting observations to how recently the snail habitat has been utilized for rice cultivation and the intensity, continuity and method of rice culture before the field investigation was conducted. According to Garcia, a 1952–55 survey in Bukidnon province, in the Philippines, found snails in intensively cultivated rice areas only in adjacent ditches or canals; in areas where fields were idle for part of the year and rice cultivation was less intensive, snail breeding occurred in the ricefields.

Impact of crop intensification

General effects on ricefield ecology

Modern technologies in wetland rice cultivation utilize fertilizer-responsive rice varieties and optimum water, nutrient and crop management practices. These technologies have very significantly increased rice yields and production in most rice-growing countries, but in many situations excessive agrochemicals are used. The environmental impacts of the use of agrochemicals have not been fully assessed. Traditional ricefields, some of which have been cultivated for several hundred years, might be considered as climax communities. In general, a disturbance to a stabilized ecosystem reduces the number of species while provoking 'blooms' of certain others. Those two effects have been observed in ricefields.

Reduction of species diversity. Reports on the fauna of traditional ricefields (Fernando, Furtado and Lim, 1979; Heckman, 1979) and records in fields subject to agrochemical use (Lim, 1980; IRRI, 1985; Roger, Grant and Reddy, 1985) show that crop intensification has led to a marked diminution of species diversity. Fernando, Furtado and Lim anticipated (1) a decrease in species diversity with intensified rice cultivation because of the disappearance of permanent reservoirs of organisms in the vicinity of the fields and disturbances of the ecosystem by mechanization and the use of pesticides, and (2) the enhancement of specific components of the fauna because of a higher algal productivity resulting from fertilizer use and an increase in particulate organic matter resulting from soil preparation. In a two-year study of the effects of pesticide application on the aquatic invertebrate community in ricefields in Selangor, Malaysia, Lim (1980) found that species diversity decreased, but pesticide application increased the overall population because, *inter alia*, of a rapid recruitment of ostracods. In surveys of 18 sites in the Philippines (IRRI, 1985) and India (Roger, Grant and Reddy, 1985), the highest number of taxa recorded at one site was 26; the lowest, two. Ostracods, chironomids and molluscs dominated the invertebrate community at most sites. By hydrobiological standards, the species diversity observed in both surveys was low. Population dominance was inversely proportional to diversity. At some sites in the Philippines, a few species attained exceptionally high densities (2 550–28 000/m^2).

It is also important to recognize that intensive rice production reduces edible species traditionally harvested from the ricefield. A study conducted in 1975 by Heckman (1979) in North Thailand shows that ricefields were used to collect a wide range of edible plants and animals; 17 edible species were collected in a single ricefield within one year (Table 2). The decline of fish catches in ricefields has been attributed to the combination of double cropping, which does not give the fish enough time to grow, and intensive use of pesticides (Lim, 1980).

Blooming of individual species. Agrochemical use, besides increasing rice yields and decreasing species diversity, frequently leads to the explosive multiplication of single species that might directly or indirectly have detrimental effects. Examples are listed by Roger and Kurihara (1988):

- Blooms of green algae and diatoms observed at the beginning of the crop after fertilizer application cause N losses by volatilization.
- Proliferation of ostracods, observed after carbofuran application, inhibits the development of efficient N_2-fixing BGA blooms.
- Very dense populations of aquatic snails develop at the beginning of the crop (observed on the

Table 2. Edible plants and animals harvested during 1975 in a Thai ricefield.

Scientific name	Common name or description
Oriza sativa	
Ipomea aquatica	Green vegetable
Pila pesmei	Large edible snail
Pila polita	Large edible snail
Macrobrachium lanchesteri	Small prawn
Somanniathelphusa sinensis	Crab
Lethocerus indicus	Large edible water bug
Channa stiata	Snakehead
Clarias batrachus	Walking catfish
Anabas testudineus	Climbing perch
Cyclocheilichthys apogon	Cyprinid
Puntius leiachantus	Cyprinid
P. stigmatosus	Cyprinid
Esomus metallicus	Cyprinid
Fluta alba	Swamp eel
Trichogaster pectoralis	Edible gourami
Macrognathus aculeatus	Spiny eel
Rana limnocharis	Frog

Source: After Heckman (1979).

IRRI farm and in many ricefields in the Philippines).

- Large populations of mosquito larvae develop in shallow-water ricefields but are absent in traditional ricefields where floodwater is deeper and predators are abundant (Heckman, 1979).

Effects on vector-borne diseases

Extension of flooded areas. Ricefields can provide appropriate breeding sites for important vectors of malaria, arboviruses, filariases, etc. An increased incidence of such diseases following the extension of wetland rice cultivation has been reported. In particular, there has been a general mosquito problem, especially proliferation of anopheline, in areas where rice cultivation has been introduced (Carnevale and Robert, 1987; Choumkov, 1983; Webbe, 1961). Rice cultivation tends to increase air humidity, which increases the longevity of mosquitoes.

On the other hand, turning swampy areas into ricefields reduces vector incidence. Snellen (1987) has cited the success of periodic drainage practices in controlling malaria in Java, Indonesia, during the Dutch colonial period. As pointed out by Najera (1988), agricultural practices were early recognized as modifiers of the malaria risk of an area, and popular wisdom recognized this potential in sayings such as 'Malaria flees before the plough.'

High crop intensity. There is evidence that both the introduction of irrigated rice and intensified cropping may increase vector-borne disease incidence. In Egypt the number of mosquito vectors declined in September when ricefields dried up, while the persistence of malaria in one region (Kalyubia governorate) was suspected to be due mainly to extensive rice cultivation (Rathor, 1987). Luh Pao-Ling (1987) observed variation patterns of adult mosquitoes coinciding with rice cropping seasons. Areas with a single cropping season exhibited a single peak of mosquito abundance, whereas areas with a double cropping season exhibited two peaks. Carnevale and Robert (1987) also observed a bimodal pattern of malaria transmission in Burkina Faso, coinciding with the rice crop cycle.

Rathor (1987) reports that the change from partial to perennial cropping due to improved methods of irrigation in upper Egypt resulted in a 30-fold increase in the percentage of the population infested with schistosomiasis. But Garcia (1988) reports that in intensively cultivated ricefields of the Philippines with at least two crops a year, snails were absent from the fields and found only in adjacent ditches and canals.

Crop intensification with crop rotation (wetland–dryland) makes possible irrigation practices that could prevent the breeding of snails, especially the amphibious species. Where *Oncomelania* is prevalent, crop rotations can control or even eradicate snails (Pesigan *et al*, 1958). Crop rotation effectively controls aquatic snails only where both the water distribution channels and the fields can be dried (Webbe, 1988).

Rice varieties. Variations in plant height and the canopy architecture of the rice cultivar affect the mosquito habitat because the degree of shading determines in part the suitability of ricefields for colonization by mosquito species and potential predators.

Irrigation of ricelands is associated with the adoption of modern, semidwarf rice cultivars, which have a shorter stature (80–100 cm) than the older cultivars (usually > 130 cm) and an erect plant type, allowing more sunlight to penetrate the canopy even though the leaf area index is high (Garrity, 1988). This may have distinct implications in vector control (Mather and Trinh Ton That, 1984), but it has not been determined whether or not canopy differences in rice cultivars have a practical effect on the colonization of mosquitoes (Garrity, 1988). However, the widely varied shade preference of *Anopheles* species gives cultivar canopy differences very little potential as a vector management tool.

Fertilizers. Urea applied as topdressing produces blooming of unicellular green algae and diatoms, which cause nitrogen losses by ammonia volatilization and provide food for vectors. Deep placement of urea supergranules in the soil and utilization of slow-release N fertilizer such as sulphur-coated urea reduce this algal growth and increase N fertilizer efficiency (Roger and Kurihara, 1988). For various reasons these methods of fertilizer application are still not widely used and their relationships to vectors have not been studied.

Pesticides. Pesticides have three major effects on vectors: (1) they temporarily decrease vector incidence, (2) they cause resurgence of resistant strains, and (3) they have adverse effects on the natural predators and competitors of vectors.

Most agricultural insecticides are non-specific; they are toxic to agricultural pests as well as to some vectors. Numerous data in the literature confirm the potential of agricultural insecticides for suppressing mosquitoes, larvae as well as adults, and their predators, through direct toxicity (Mulla and Lian, 1981). Herbicides, fungicides and molluscicides appear to possess limited toxicity in insects at the concentrations in which they are applied in the field (Georghiou, 1987).

Among the probable explanations for the marked reduction of malaria and Japanese encephalitis in Japan since 1945, Self (1987) lists the significant reduction of vector populations through the extensive use of insecticides for agricultural purposes. Similarly, Mogi (1987) attributes the reduction of mosquito vectors in Japanese ricefields in the late 1960s to the intensive application of organophosphorous and carbamate insecticides. However, Self (1987) indicates that in Korea pesticide application for agricultural purposes reduced the density of the Japanese encephalitis vector *Culex tritaeniorhyncus* in rice-growing areas, but had no effect on the main malaria vector *Anopheles sinensis*.

In the rice-growing areas in the USA the elimination of malaria by suppressing the vector with DDT in the period afer the Second World War led the way to extensive insecticide use against both mosquitoes and agricultural pests. Chlorinated hydrocarbon, organophosphate, carbamate and, more recently, synthetic pyrethroid insecticides have been used extensively enough in the USA to have produced resistance in some riceland mosquitoes. Experience has shown that mosquito populations are particularly adapted to evolving resistant strains. Resistance arises because some individuals within the population already possess a genetic make-up that confers resistance on them before they are exposed to any insecticides (Mather and Trinh Ton That, 1984). Observations with upland crops show a strong correlation between the intensity of pesticide use on crops and the degree of extended vector resistance. In 1987, 50 malaria vectors resistant to one or more pesticides were recorded in the world (Bown, 1987).

Flooded rice soil is an ideal environment for rapid detoxication of many pesticides. Degradation is usually faster in flooded soils than in non-flooded soils and other aerobic systems (Sethunathan and Siddaramapa, 1978). However, many agricultural insecticides sprayed in ricefields affect not only rice pests but also some vectors, predators or competitors, thus decreasing species diversity and causing blooming of individual species, especially ostracods, mosquito larvae and molluscs. In a field trip in India, Roger, Grant and Reddy (1985) observed that mosquito larvae and molluscs (*Limnea* and *Vivipara*) were either dominant or abundant in gamma BHC-treated plots. Molluscs are usually not affected by conventional rice pesticides and their populations rapidly increase because of reduced competition for energy sources. Population densities of *Lymnaea sp.* may reach 1000/m^2 in Philippine ricefields and the biomass of snails ranges from a few kilogrammes to 1.5 tonnes fresh weight per ha at IRRI (IRRI, 1981). The decrease of *C. tritaeniorhynchus* after 1970 in Japan is perhaps due, in part, to the increase of its natural enemies by the switch from chlorinated hydrocarbons to carbamates that do not adversely affect vector predators (Mogi, 1978; Wada, 1974).

Agricultural labour. Agricultural development, resulting in better socioeconomic conditions, attracts labourers from less favoured areas, and they may be a source of parasites or diseases. Rathor (1987) gave some examples of this process for the eastern Mediterranean region. Self (1987) reported that on Hainan Island, China, malaria peaks in June. The outbreak occurs among immigrants engaged in agricultural work within a few months of arrival, but is rare among the local immune inhabitants.

Other agricultural practices

Straw mulching. In recent experiments at IRRI (Roger *et al*, unpublished), straw applied in the floodwater two weeks before incorporation and rice transplanting markedly increased populations of snails, which were almost absent in the control plots.

Mechanization and new implements. As pointed out by Service (1977), very little information is available on the effects of mechanization on vector populations. Available data suggest that practices such as ploughing prior to flooding (Owens *et al*, 1970) and ploughing followed by disking (Cooney *et al*, 1981) could control floodwater mosquitoes by burying mosquito eggs. Increased ploughing or disking of ricefields can make the habitat unsuitable for snails (Ito, 1970). Use of a rotary hydrotiller on a soil with about 1 cm standing water has reduced populations of large snails (*P. canaliculata*) by at least 50% (Manaligod and Quick, IRRI, personal communication).

Direct seeded rice. In direct seeded rice, mosquito reproduction begins only when the established seedlings are flooded, and it peaks during the four-week post-flooding period (Mather and Trinh Ton That, 1984). Closure of the canopy takes place earlier than in transplanted rice. The implications for vector habitat have not yet been assessed.

Synchronous planting and harvesting. A mosaic of fields planted at different times provides a continuous sequence of crops which allows pest populations to build up. Synchronous planting and harvesting in large areas have been highlighted as a means of creating off-season areawide breaks in cropping, which disturbs the life cycle of rice pests (Perfect, 1986). Synchronous planting with large areas under periodic non-crop unirrigated phases will also upset the breeding sequence of vectors (Way, 1987). From a practical point of view, however, synchrony in planting is extremely difficult to achieve in small farmholding communities, particularly because water availability is often asynchronous, and farmers are not ready with other inputs to start the crop all at the same time. Because new varieties lack photoperiod sensitivity, they allow individual timing of planting, which acts against the promotion of synchronous planting.

Weed control and flood fallow. Weed control in ricefields and related water bodies can sometimes reduce the distribution and abundance of intermediate snail hosts of schistosomiasis and mosquito vectors. For example, certain species of *Potamogeton* provide good surfaces for feeding and egg laying by *Biomphalaria truncatus* and *B. alexandria* (WHO, 1973). Algae, combined with decaying vascular plants, generally provide the best food for snail hosts. Several aquatic weeds, such as *Pistia* and *Salvinia*, furnish highly favourable habitats for *Mansonia* mosquitoes. Often these weeds are not found so much in the ricefields but in the irrigation channels, ditches and water reservoirs.

Repeated ploughing, harrowing and weed incorporation will render the ricefields less suitable for snail and mosquito populations. However, some mosquito species, such as *A. gambiae* and *A. arabiensis* in Africa and *A. culicifacies* in India, are commonly found in the turbid water created by puddling (Mather and Trinh Ton That, 1984).

Fallow fields flooded before ploughing and rice nurseries produce high densities of *A. culicifacies* in India. Subsequent cultural operations such as ploughing reduce densities, and the species generally does not occur after the rice plants reach a height of 30 cm (Russell, Knipe and Rao, 1942).

Vector control

Water management

Technically promising methods of water management for controlling vectors in ricefields include (1) alternate wetting and drying, (2) maintaining soil saturation, and (3) quick flushing. Of the three, the alternate wetting and drying method seems most promising.

Maintaining soil saturation, and thus avoiding accumulation of stagnant water on the soil, could be a water-efficient method of rice production that provides vector control, but it is technically very difficult to achieve in the field. It requires fields that are very well levelled throughout the season; farmers' activities in the field leave many small depressions and will negate the effort. It also requires precise and very frequent applications of irrigation water, which is almost impossible to achieve in practical field conditions (Bhuiyan and Shepard, 1987).

Likewise, the quick flushing method as described by Amerasinghe (1987) for removing the vector larvae periodically also suffers from the stringent requirement of well-levelled land, free of depressions, and a water control infrastructure for effective flushing of the ricefield. Furthermore, flushing requires substantial extra water, which cannot be obtained in most irrigation systems during the water-short dry season.

Alternate wetting and drying. Periodic drying off and subsequent flooding of fields during the cropping season have been recommended to control hemipterous pests such as *Nilaparvata lugens* (FAO/UNEP, 1982). These procedures would be equivalent to controlling vectors by intermittent or wet irrigation (Mather and Trinh Ton That, 1984; Lu Baolin, 1988). The Panel of Experts on Environmental Management for vector control recommended (FAO, 1987) that this technique be called alternate wetting and drying. The alternation of submerged and dried phases must be such that mosquito vectors will be either flushed or dried out before successfully completing immature development (Amerasinghe, 1987), a period that can be as short as five days for *Similium* spp (Cairncross and Feachem, 1983).

The alternate wetting and drying method of water management has been reported to require 30–50% less irrigation water than the conventional method of maintaining shallow (5–7 cm) submergence throughout the season (Bhuiyan, Kanbafwamy and Wei, 1988). The saving in water results mostly from reduced percolation rates. However, if water from the ricefield is regularly drained off rather than used up to create the dry condition, the total water required will be higher, and may even exceed that needed for the conventional continuous shallow submergence.

The alternate wetting and drying method will have a better chance of farmer acceptance if it is integrated with other measures for water conservation and vector control, assuming there is no negative effect on yield. However, reports on the effects of such irrigation methods on yield are contradictory. Hill and Cambournac (1941) described a field trial of intermittent irrigation of ricefields, showing that (1) rice quality and quantity did not suffer, (2) there was usually some yield increase and considerable savings in water, and (3) anopheline larvae were reduced by more than 80%. Some other reports show an increase in yield (Cairncross and Feachem, 1983; Luh Pao-Ling, 1984; Self and De Datta, 1988) and others a decrease (IRRI, 1987; IIMI, 1986), especially under drying periods of more than five days. The reports on yield loss are mostly from areas in the Asian tropics with relatively low fertilizer use and high temperature regimes. Such conditions reduce the production of toxic substances in the soil and hence the benefits from drying are low or non-existent. More research on this issue is going on at the IRRI and other places.

Alternate wetting and drying carried out in large areas of Henan province in east China reportedly conserved water, increased yield and resulted in reduced densities of *Anopheles maculatus* and *Culex*, vectors of Japanese encephalitis (Self, 1987). Field trials have shown this practice to be effective in both snail and mosquito control (Amerasinghe, 1987). In the Philippines, replacing continuous flooding by alternate wetting and drying on a 10-day rotation regime reduced snails from 200/m^2 to less than 1/m^2 (Cairncross and Feachem, 1983). A 90% reduction in mosquito larvae was reported in China when the method was applied in experimental fields (Luh Pao-Ling, 1984).

For optimal control, alternate wetting and drying must be practised simultaneously in all ricefields in a large area during the entire cultivation season under conditions favourable to rapid drying (Amerasinghe, 1987). To be effective, the method requires a highly organized system of water application and strict adherence to the designed schedule. A major practical limitation of the method in most irrigation systems is the unreliable supply of irrigation water, which introduces the additional risk of drought damage to fields that allow drainage of irrigation water (or rainfall) for vector control (Bhuiyan and Shepard, 1987).

The method is not efficient for the control of all vectors. For example, the operculum of *Oncomelania* enables it to survive for more than a week without surface water (Garcia, 1988) and many gastropod species undergo prolonged estivation and hibernation. Another problem accompanying drainage and drying of the ricefield is the adverse effect it may have on non-target organisms, including aquatic predators.

Importance of irrigation system management. Vectors are not restricted to the ricefield. Water management in the ricefields for vector control will be of limited use if the irrigation system management method is not modified to control vectors that breed outside the ricefields but within the system's command.

Much has been written about the breeding habitats of snails and mosquitoes provided by irrigation systems, including canals with vegetation, stagnant pools created in depressed areas due to seepage from unlined canals, dead storage in canals, burrow pits, choked drainage ditches, etc. Speelman and van den Top (1986) identified specific breeding sites of mosquitoes in a Sri Lankan irrigation system. Irrigation system areas outside the rice crop fields are considered very important breeding grounds of schistosome snails. It is doubtful whether many farmers become infected by the parasite during land preparation, weeding or harvesting. Garcia (1988) concludes that more farmers probably become infected while washing in irrigation canals than while working in ricefields.

Most snails feed on vegetation. There is a direct correlation between snail populations and the density of aquatic vegetation; therefore feeder canals should be free of weeds to prevent explosive growth of snail populations. The weed provides not only food for the snails but an egg-laying surface and cover for the hatchlings (Gaddal, 1988).

Biological control

Biological control of vectors has basically two major approaches: (1) conserving natural predators and maintaining species diversity, and (2) introducing new predators (fish or insects), competitors and parasites (microorganisms or nematodes). We also consider here the possible utilization of pesticides of plant origin.

Conserving natural predators. The traditional ricefield ecosystem is biologically diverse. Although many vectors can exist in the ecosystem, the complexity of animal populations and predator pressure limit productivity of any one vector. In contrast, strict rice monoculture will have a less diverse fauna, and, without control measures, the productivity of a few key vectors may be extremely high. The insecticides needed to manage this situation may create secondary problems (Bradley, 1988).

Most of the information on conservation of natural predators refers to mosquitoes and shows that some natural enemies play an important role in reducing the number of mosquito vectors, at least under certain circumstances (Mogi, 1978; Wada, 1974). For example, the number of adults produced from 3300 first-instar larvae of *C. tritaeniorhynchus*, placed in each of three experimental plots, ranged from 0 to 144. The number of *Odonata* nymphs and *Notonectidae* nymphs and adults was larger in the plot from which fewer adults emerged, indicating their importance as natural enemies (Mogi, Mori and Wada, 1980 a, b).

Survival of mosquito larvae in ricefields from the first-instar through the pupal stage varies from 2 to 5% (Mogi, Mori and Wada, 1980 a, b; Northup and Washino, 1983; Service, 1977). Much of the natural mortality is attributed to predators: fish, *Odonata, Notonectidae* and *Discidae* (Miura *et al*, 1978; Mogi, 1978; Service, 1975; Washino, 1981). Spiders were also important in reducing the number of adult mosquitoes (Wada, 1988). It is, however, difficult to determine which predators or groups of predators are the most important, and this may vary considerably from one geographic area to another (Dame, Washino and Focks, 1988).

Although predators of mosquito larvae may well be causing 90% or more mortality of the immatures, there may still be large numbers of mosquitoes emerging and constituting a nuisance or disease hazard. However, if these natural predators are destroyed then the numbers of emerging mosquitoes are likely to be even greater, and so, even if it is not envisaged that invertebrate predators can be exploited as biological control agents, cultural practices favouring their existence should be encouraged (Mather and Trinh Ton That, 1984).

Fish. Food fish have served, intentionally or not, for the control of vectors in many Asian countries. In China, raising grass carp and other fish in ricefields led to an 80–90% reduction in the density of mosquitoes and their larvae in rice-growing areas in Henan province. Grass carp ingested about 400 mosquito larvae per day (Anon, 1984, cited by Petr, 1987). Among various agriculture-related vector-control practices used in China, Self (1987) reports community collaboration with fisheries personnel in rearing and releasing of fish (*Tilapia, Ctenopharyngodon, Cyprinus*, etc) in channels and in and around ricefields. In consequence weeds have been consumed, rice yields have increased partly because of the fish excreta, and the grown fish have provided food. The exotic tilapia *Oreochromis niloticus*, now widely used in tropical Southeast Asia, is also an efficient larvivore. In the Philippines, with supplementary feeding, the combined culture of larvivorous tilapia and common carp in ricefields has given a fish yield of 692 kg/ha/yr (Petr, 1987).

According to Dame, Washino and Focks (1988) *Gambusia affinis* or mosquito fish is still the only demonstrated biological control agent presently used in the USA for ricefield mosquito control. The fish is introduced each year into ricefields shortly after initial flooding. Once established, several broods may be produced during the summer months. Approximately 750 fishes/ha give an effective control (Hoy, O'Berg and Kaufmann, 1971). Stocking fields 15–25 days after rice seeding appears to give the best fish population growth and mosquito control (Farley and Younce, 1977). Haas and Pal (1984) reported that *G. affinis* effectively controls mosquitoes because it (1) easily penetrates shallow, weedy areas, (2) is primarily carnivorous, but becomes omnivorous when food is scarce, (3) has a dorsal mouth and frequents the surface, (4) bears live young, and (5) tolerates salinity, high temperature and moderate organic pollution.

Black carp (*Mylopharyngodon piceus*) and common carp (*Cyprinus carpio*) can be used for controlling snails (Mochida, 1988).

However, agricultural practices for modern varieties may not be compatible with the use of ricefields for simultaneous fish production. The principal constraints to ricefield fisheries and to the use of fish for vector control in ricefields are the toxicity of agrochemicals, especially pesticides, and an unreliable water supply. In 1987 one of the recommendations of the Panel of Experts on Environmental Management for vector control (FAO, 1987) was to investigate whether the high pesticide input in ricefields might have led to a lower fish yield as compared with that from ricefields with a lower pesticide level usually associated with the growing of traditional varieties.

The use of *G. affinis* in ricefields has been criticized by several authors. It has been effective against *Culex tarsalis* in California ricefields, but its effectiveness against *Anopheles* spp is questionable (Hoy, O'Berg and Kaufmann, 1971). Farley and Younce (1977) considered it a rather poor controlling agent as it preys to a large extent on non-target organisms such as crustaceans and chironomids. As it preys on the eggs of other fish its introduction might reduce indigenous fish species (Schaefer and Meisch, 1988). Also, the fish appeared to prefer the deeper open portions of water in the ricefields, while mosquito larvae were most abundant in the shallow protected areas of the field. Thus, the predator and prey were isolated from each other ecologically (Reed and Bryant, 1972). *Gambusia* invaded parts of Japan and drove a native fish, occupying the same ecological niche, almost completely out of the ricefields. Therefore it added little to the role of natural enemies in mosquito control (Wada, 1988).

Experience in the efficiency of larvivorous exotic fish has been varied, and Mather and Trinh Ton That (1984) expressed the opinion that there is little real evidence that introducing fish into habitats already colonized by a rich fauna of natural predators has really led to any worthwhile reduction in disease transmission. Indigenous larvivorous fish have been found to be highly effective in mosquito control. Such fish are well adapted to local conditions and are readily available for mass rearing and dissemination.

This underscores the importance of careful studies before introducing any exotic natural enemies. The most promising concept is obviously to stock fields with larvivorous fish that could later be harvested for food. Research is needed to identify indigenous species more suited to the ricefields of individual countries.

Insect predators. Probably the least attention to date has been given to insect predators. Numerous aquatic predator species occur in most ricefields, but their potential for mosquito control for most parts of the world is unknown. Their taxonomy and ecology need to be studied before their possible use in integrated control can be assessed and ways of multiplying them evaluated (Schaefer and Meisch, 1988).

Animal competitors. The use of competitors is a strategy that seems to have been restricted to snail vectors. The use of competitor snails, *Marisa cornuarietis* and *Thiara*, to supplant schistosome vector snails has been reported to be successful in ponds and canals (Gaddal, 1988). *M. cornuarietis* is a large ampullarid that has been used successfully in Puerto Rico in large ponds as a competitive feeder and incidental predator on *Biomphalari glabrata*. Recent reports suggest that *Marisa* has replaced *B. pfeifferi* in an aquatic habitat in Tanzania and in the canals of the Gezira scheme, in Sudan, where it has successfully survived more than 18 months (Gaddal, 1988). Conversely, *M. cornuarietis* has been reported to destroy newly transplanted rice seedlings (Gaddal, 1988), but Bergquist and Chen Ming-Gang (1988) consider the danger to rice seedlings to have been exaggerated. Also the snail is not particularly resistant to drying out of its habitat during prolonged periods (Nguma, McCullough and Masha, 1982). Therefore Mather and Trinh Ton That (1984) consider *Marisa* use to control snail vectors in rice irrigation to be neither proven nor recommended.

Thiara is reported to have been responsible for the decline in *B. glabrata* populations in certain West Indies islands, and the mechanism of replacement by this apparently harmless snail deserves further study. Another snail with the potential to replace the schistosome vectors in certain African field situations is *Helisoma duryi*, which may use a combination of competition and growth-inhibiting factors to replace snails in freshwater habitats (Gaddal, 1988).

The reduction of the snail population by introducing sterile males has not shown promise (Garcia, 1988).

Azolla. Azolla grows rapidly and under favourable conditions can cover a given water surface completely within 10 days. The potential inhibitory effect of water surface coverage by azolla on mosquito breeding was suggested in China as early as 1934 by Li and Wu. Laboratory studies of the effect of azolla on mosquito breeding show that complete coverage of the water surface by azolla is needed to inhibit oviposition of *Culex* spp (Lu Baolin, 1988). On the other hand, azolla is a good source of food for snails.

It is highly unlikely that azolla will be used as a method for mosquito control only. Mosquito control is rather an additional benefit in areas where azolla is used as green manure.

Microbial agents. Microbial agents with a potential to control mosquitoes include viruses, bacteria and fungi (Lacey and Undeen, 1986). *Bacillus thuringiensis* serotype H-14 (sometimes designated H-14 or Bti) has been the most studied agent. It can provide selective control of mosquito larvae, causing relatively little harm to most of the predators of vectors and agricultural pests (Way, 1987). The application of Bti to ricefields in Louisiana, USA, is often accomplished by a drip technique, which is calibrated to match the flow of irrigation water into the fields. Thus the bacterial spores containing the toxin are present when the vector larvae of *Psorophora* hatch shortly after flooding. The level of control is usually high except in areas where the hydrological characteristics of the field restrict water movement. Because the vector hatches in response to flooding, the brood can be controlled by a single treatment of about 1.2 l/ha (McLaughlin and Vidrine, 1984).

Other microbial agents with a potential to control malaria vectors include *Bacillus sphaericus*, fungi such as *Culicinomyces clavisporus, Lagenidium giganteum, Tolypocladium cylindrosporum* and *Coelomomyces* spp, and viruses such as baculoviruses (Cowper, 1988).

The high levels of mortality produced by several virulent strains of *B. sphaericus* in several culicine and anopheline larvae without undue effect on non-target organisms, and the persistence of its larvicidal activity, make it a viable candidate for testing in ricefields (Dame, Washino and Focks, 1988).

The genera of fungi *Coelomomyces, Lagenidium* and *Culicinomyces* have the ability to recycle and are efficacious in the field. *Lagenidium* and *Culicinomyces* also offer the advantage of being culturable on artificial media. *Lagenidium giganteum* Couch has been successfully field-tested in ricefields in California (Kerwin and Washino, 1986a) and, to a lesser extent, in Arkansas (Dame, Washino and Focks, 1988).

Nematodes. Some nematodes have a potential to control malaria vectors, especially *Romanomermis culicivorax*. Because of its demonstrated recycling and apparent resistance to desiccation during winter, it has been investigated in California ricefields (Kerwin and Washino, 1986b; Westerdahl, Washino and Platzer, 1982). Minimal parasite dispersal from the point of application in ricefields (limited to within 12 m of a single release point) as well as the labour required for mass rearing *in vivo* renders this approach impractical now (Dame, Washino and Focks, 1988; Schaefer and Meisch, 1988).

Pesticides of plant origin. Many studies have shown that oil from the seed kernel of the neem tree *Azadirachta indica* reduces feeding on rice plants by leafhoppers, planthoppers and leaf-folders (Saxena, 1989), as well as grazing of BGA by ostracods (Grant, Roger and Watanabe, 1985). Another oil derived from the custard apple (*Annona* spp) also acts as an antifeedant to several rice pests. For years in some Asian countries these products have been employed in a crude form as mosquito repellents; more recently, neem oil has been shown to be capable of affecting and even killing mosquito larvae (Mather and Trinh Ton That, 1984; Zebitz, 1986; Saxena, 1989). A possible problem with plant material used directly as a pesticide is the variability of the properties that depend upon the growth conditions and the time and methods of harvest and conservation. Inconsistent effects of neem seed applications have been obtained in the experiments conducted at the IRRI to control ostracods that feed on BGA (Roger *et al*, unpublished.)

Other pesticides of plant origin have been reported to control microcrustaceans and molluscs economically. Nuts, berries or shells of *Phytolacca dodecandra, Croton tiglium* and *Anacardium occidentalis* reportedly controlled some snail populations (McCullough *et al*, 1980; Webbe and Lambert, 1983). Hostettmann (1984) reported that approximately 50 molluscicidal compounds have so far been isolated from plants; they include saponins, terpenoids, flavonoids, naphtoquinones and tannins. However, Gaddal (1988) pointed out that while in the 1970s plant molluscicides were thought to be the answer to snail control and that rice-growing countries would be able to produce their own, at present, however, enthusiasm for the two main candidate molluscicides in this category, *Phytolacca dodecandra* and *Damsissa*, has waned in Africa.

The wide range of plants exhibiting insecticidal or molluscicidal properties offers a cheap alternative for vector control which is underexploited.

Conclusions

Inadequate knowledge of the role of ricefields. Concern about vector-borne diseases is not recent, but quantitative data on the contribution of ricefields to their transmission in different environments are very limited. As a result, many speculative conclusions have appeared in the literature. Given the severity and extensiveness of these diseases, the importance of rice culture in the tropics and the foreseeable expansion of irrigated rice, a better understanding of the magnitude of the problem in ricefields themselves and the vectors' relationships with various rice cultural practices is imperative. This is essential before any recommendations can be made on possible control measures in the ricefield *vis-à-vis* its surroundings and supporting irrigation network.

Potential adoption of control measures. It is highly improbable that rice farmers will adopt measures designed to control vectors only. To be attractive, vector control practices should be part of cultural practices that show tangible benefits in terms of yield increase or reduced input.

Conservation of natural enemies of vectors. In many areas farmers are found to use more pesticides than are required for controlling rice pests. While natural biological control is not expected to prevent pest damage entirely, there is sufficient evidence that destruction of the natural populations of predators through overuse of pesticides can lead to major problems such as the development of undesirable vector species and of pest resistance.

With regard to the potential of food-fish for controlling vectors, it is important to investigate rice cultural practices, including methods of pesticide use, that are compatible with fish culture.

More research on the conservation of environmental conditions that sustain natural enemies of vectors is also needed.

Water management for control. Among the possible methods of water management for vector control in ricefields, the alternate wetting and drying method seems more promising than the others because of its potential for water saving. However, the method will also affect natural predators and competitors of the vectors. There is a need to establish the yield relationship of alternate wetting and drying for various soil types and environmental conditions. The cost of water control infrastructure needed in the fields for implementing such a method may not be very high, but for sustained success it will require a level of farmer organization and institutional support currently not available in most tropical rice irrigation systems.

Biological control. The potential of biological control has wide appeal to field biologists, but no method has yet been sufficiently evaluated to be recommended.

Among possible methods, the most promising for small farmholders is obviously to stock ricefields with larvivorous fish that could later be harvested for food. Research is needed to identify the fish species most suitable to the ricefields in individual countries. In addition, there is a need to develop pest management technologies, including minimum doses of pesticides when essential, which are compatible with fish culture.

It seems that mosquito control by *Bacillus thuringensis* has had some success in the USA. The efficacy and economics of the technique should be tested under tropical conditions.

References

Amerasinghe, F.P. (1987). 'Change in irrigation techniques as a means to control disease vector production', pp 82–86 in *Effect of Agricultural Development on Vector-Borne Diseases*, FAO AGL/MISC/12/87, proceedings of the 7th annual meeting of the joint WHO/FAO/UNEP PEEM, 7–12 September 1987, FAO, Rome.

Bergquist, N.R., and Chen Ming-Gang (1988). 'Control of schistosomiasis: research aspects', pp 133–141 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Bhuiyan, S.I., P. Kanbafwamy and Z. Wei (1988). 'Efficient irrigation water management for rice and upland crops', International Rice Research Conference papers, IRRI, Manila, the Philippines.

Bhuiyan, S.I., and B.M. Shepard (1987). 'Modern rice technology and its relationships to disease vector propagation', pp 10–17 in *Effect of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Bown, D. N. (1987). 'Agricultural use of pesticides and their effect on vector-borne disease transmission in the WHO region of the Americas', pp 53–56 in *Effect of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Bradley, D.J. (1988). 'The epidemiology of ricefield-associated diseases', pp 29–39 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Cairncross, S., and R.G. Feachem (1983). *Environmental Health Engineering in the Tropics: An Introductory Text*, John Wiley, Chichester, UK.

Carnevale, P., and V. Robert (1987). 'Introduction of irrigation in Burkina Faso and its effects on malaria transmission', pp 57–67 in *Effect of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Choumkov, M. (1983). 'Méthode de lutte biologique contre les moustiques dans les conditions de développement intensif de la culture irriguée', pp 203–215 in *La Lutte contre le paludisme*, tome II C. Est, Moscou (cited by Carnevale and Robert, 1987).

Coche, A.G. (1967). 'Fish culture in ricefields: a world-wide synthesis', *Hydrobiologia*, Vol 30, pp 1–44.

Cooney, J.C., E. Pickard, J.W. Upton and B.R. McDuff (1981). 'Tillage, a nonchemical method for the control of floodwater mosquitoes', *Mosquito News*, Vol 41, pp 642–649.

Cowper, T. (1988). 'Malaria vectors associated with rice culture in Southeast Asia and the Western Pacific', pp 84–92 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Dame, D.A., R.K. Washino and D.A. Focks (1988). 'Integrated mosquito vector control in large-scale rice production systems', pp 184–196 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP, Manila, the Philippines.

De Datta, S.K. (1981). *Principles and Practices of Rice Production*, John Wiley, New York.

FAO (1987). *Effects of Agricultural Development on Vector-Borne Diseases*, AGL/MISC/12/87, FAO, Rome.

FAO/UNEP (1982). *Integrated Pest Control in Agriculture*, reports of the 11th session of the FAO/UNEP Panel of Experts Meeting, Kuala Lumpur, Malaysia, 5–10 March, FAO, Rome.

Farley, D.G., and L.C. Younce (1977). 'Stocking date *versus* efficacy of *Gambusia affinis* in Fresno County ricefields', *Proceedings of the California Mosquito Control Association*, Vol 45, pp 83–86.

Fernando, C.H., J.I. Furtado and R.P. Lim (1979). *Aquatic Fauna of the World's Ricefields*, Wallanaceana Suppl 2, Department of Zoology, University of Malaya, Kuala Lumpur, Malaysia.

Gaddal, A.A. (1988). 'Control of the *Schistosoma mansoni* and *S. haematobium* intermediate hosts in ricefields', pp 211–215 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Garcia, E.G. (1988). 'Control of *Schistosoma japonicum* snail intermediate host in riceland agroecosystems', pp 202–210 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Garrity, D.P. (1988). 'Tropical rice agroecosystems: characteristics, distribution, and future trends', pp 13–28 in *Vector-Borne Disease Control in Humans Through Rice*

Agroecosystem Management, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Georghiou, G.P. (1987). 'The effect of agrochemicals on vector populations', pp 101–106 in *Effects of Agricultural Development on Vector-Borne Diseases*, AGL/MISC/12/87, FAO, Rome.

Goonasekere, K.G.A., and F.P. Amerashinge (1988). 'Planning, design, and operation of rice irrigation schemes – their impact on mosquito-borne diseases', pp 41–50 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Grant, I.F., P.A. Roger and I. Watanabe (1985). 'Effect of grazer regulation and algal inoculation on photodependent N_2 fixation in a wetland rice field', *Biology and Fertility of Soils*, Vol 1, pp 61–72.

Grant, I.F., P.A. Roger and I. Watanabe (1986). 'Ecosystem manipulation for increasing biological N_2 fixation by blue-green algae (Cyanobacteria) in lowland rice fields', *Biological Agriculture and Horticulture*, Vol 3, pp 299–315.

Gratz, N.G. (1988). 'The impact of rice production on vector-borne disease problems in developing countries', pp 7–12 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Haas, R., and R. Pal (1984). 'Mosquito larvorous fish', *Bulletin of the Entomological Society of America*, Vol 30, pp 17–25.

Harwood, R.F., and M.T. James (1979). *Entomology in Human and Animal Health*, MacMillan, New York.

Heathcote, O.H.U. (1970). 'Japanese encephalitis in Sarawak, studies on juvenile mosquito populations', *Transactions of the Royal Society of Tropical Medicine and Hygiene*, Vol 64, pp 483–488.

Heckman, C.W. (1979). 'Rice field ecology in northeastern Thailand. The effect of wet and dry seasons on a cultivated aquatic ecosystem', *Monographiae Biologicae*, Vol 34.

Hill, R.B., and F.J.C. Cambournac (1941). 'International irrigation in rice cultivation, and its effects on yield, water consumption, and *Anopheles* production', *American Journal of Tropical Medicine*, Vol 21, pp 123–144.

Hostettman, K. (1984). 'On the use of plants and plant-derived compounds for the control of schistosomiasis', *Naturwissenchaften*, Vol 71, pp 247–251.

Hoy, J.B., A.G. O'Berg and E.E. Kaufmann (1971). 'The mosquitofish as a biological control agent against *Culex tarsalis* and *Anopheles freeborni* in Sacramento Valley ricefields', *Mosquito News*, Vol 31, pp 567–572.

ICLARM and SEARCA (1986). *Integrated Agriculture-Aquaculture Farming Systems*, ed R.S.V. Pullin and Z.H. Shehadeh, ICLARM, Manila, the Philippines.

IIMI (1986). *Annual Report for 1984–85*, International Irrigation Management Institute, Digana Village, Sri Lanka.

IRRI (1981). *Annual Report for 1980,* IRRI, Manila, the Philippines.

IRRI (1985). *Annual Report for 1984*, IRRI, Manila, the Philippines.

IRRI (1987). *Annual Report for 1986*, IRRI, Manila, the Philippines.

Ito, Y. (1970). 'Ecological studies on *Oncomelania nosophora*, the intermediate host snail of *Schistosoma japonicum* in the rice fields', *Japanese Journal of Parasitology*, Vol 19, pp 494–507.

Kerwin, J.L., and R.K. Washino (1986a). 'Ground and aerial application of the sexual and asexual stages of *Lagenidium giganteum* (Oomycetes: Lagenidiales) for mosquito control', *Journal of the American Mosquito Control Association*, Vol 2, pp 182–189.

Kerwin, J.L., and R.K. Washino (1986b). 'Recycling of *Romanomermis culicivorax* (Mermithidae, Nematoda) in ricefields in California', *USA Journal of Medical Entomology*, Vol 22, pp 637–643.

Kung, P. (1971). *Irrigation Agronomy in Monsoon Asia*, FAO, Rome.

Kurasawa, H. (1956). 'The weekly succession in the standing crop of plankton and zoobenthos in the paddy field. Parts 1 and 2', *Miscellaneous Reports of the Research Institute for Natural Resources (Tokyo)*, Vol 4, Nos 41/42, pp 86–98, and Vol 4, No 45, pp 73–84 (in Japanese).

Kurihara, Y., and K.I. Kadowaki (1988). 'Effect of different ecological conditions on the mud snail (*Cipangopaludina japonica*) in submerged paddy soil', *Biology and Fertility of Soils*, Vol 6, No 4, pp 292–297.

Kurihara, Y., T. Suzuki and K. Moriyama (1987). 'Incorporation of heavy metals by the mud snail *Cipangopaludina chinensis malleata* Reeve, in submerged paddy soil treated with sewage sludge', *Biology and Fertility of Soils*, Vol 5, pp 93–97.

Lacey, L.A., and A.H. Undeen (1986). 'Microbial control of black flies and mosquitoes', *Annual Review of Entomology*, Vol 31, pp 265–295.

Li Feng Shen and Wu Xi Cheng (1934). *Methods for Mosquito Control*, Commercial Press, Shanghai (in Chinese).

Lim, R.P. (1980). 'Population changes of some aquatic invertebrates in ricefields', pp 971–980 in *Tropical Ecology and Development*, Proceedings of the 5th International Symposium of Tropical Ecology, International Society of Tropical Ecology, Kuala Lumpur, Malaysia.

Lu Baolin (1988). 'Environmental management for the control of ricefield-breeding mosquitoes in China', pp 110–121 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Luh Pao-Ling (1984). 'The wet irrigation method of mosquito control in ricefields: an experience of intermittent irrigation in China', pp 133–136 in *Environmental Management for Vector Control in Ricefields*, FAO, Rome.

Luh Pao-Ling (1987). 'Effect of rice growing on the population of disease vectors', pp 130–132 in *Effect of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Mather, T.H., and Trinh Ton That (1984). *Environmental Management for Vector Control in Ricefields*, Irrigation and Drainage Papers No 41, FAO, Rome.

McCullough, F.S., Ph. Gayral, J. Duncan and J.D. Christie (1980). 'Molluscicides in schistosomiasis control', *Bulletin of the WHO*, Vol 58, pp 681–689.

McLaughlin, R.E., and M.F. Vidrine (1984). 'Point-source introduction system for control of *Psorophora columbiae* (Diptera, Culicidae) by *Bacillus thuringiensis* serotype H14: results of a large area operation test', *Environmental Entomology*, Vol 13, pp 366–370.

Miura, T., R. M. Takahashi and F. S. Mulligan (1978). 'Field evaluation of the effectiveness of predaceous insects as mosquito control agent', *Proceedings of the California Mosquito Control Association,* Vol 40, pp 80–81.

Mochida, O. (1988). 'Nonseedborne rice pests of quarantine abundance', pp 117–129 in *Rice Seed Health*, IRRI, Manila, the Philippines.

Mogi, M. (1978). 'Population studies on mosquitoes in the ricefield area of Nagasaki, Japan, especially on Culex tritaeniorhynchus', *Tropical Medicine*, Vol 20, pp 173–263.

Mogi, M. (1987). 'Effect of changing agricultural practices on the transmission of Japanese encephalitis in Japan', pp 93–100 in *Effect of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Mogi, M. (1988). 'Water management in rice cultivation and its relation to mosquito production in Japan', pp 101–109 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI, Manila, the Philippines.

Mogi, M., A. Mori and Y. Wada (1980a). 'Survival rates of *Culex tritaeniorhynchus* (Diptera, Culicidae) larvae in fallow ricefields before summer cultivation', *Tropical Medicine* (Nagasaki), Vol 22, pp 47–59.

Mogi, M., A. Mori and Y. Wada (1980b). 'Survival rates of immature stages of *Culex tritaeniorhynchus* (Diptera, Culicidae) in ricefields under summer cultivation', *Tropical Medicine* (Nagasaki), Vol 22, pp 111–126.

Moroni, A. (1961). 'L'ecosystema di risaia', *(Monografia) Annali della Facolta Agraria Universita Cattolica del Sacro Cuore*, Vol 31, pp 8–53.

Muirhead-Thomson, R.C. (1951). *Mosquito Behaviour in Relation to Malaria Transmission and Control in the Tropics*, Edward Arnold, London.

Mulla, M.S., and M.L.S. Lian (1981). 'Biological and environmental prospects of the insecticide malathion and parathion on non-target biota in aquatic ecosystems', *Residue Reviews*, Vol 7, pp 121–173.

Najera, J.A. (1988). 'Malaria and rice: strategies for control', pp 123–132 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Nguma, J.F.M., F.S. McCullough and E. Masha (1982). 'Elimination of *Biomphalaria pfeifferi, Bulinus tropicus*, and *Lymnea natalensis* by the ampullaria snail *Marisa cornuarietis*, in a man-made dam in northern Tanzania', *Acta Tropica*, 3985–3990.

Northup, J.O., and R.K. Washino (1983). 'A field larval table for *Anopheles freeborni*', *Proceedings of the California Mosquito Vector Control Association*, Vol 51, p 79.

ODA (1984). 'N_2-fixation in deep-water ricefields of Bangladesh', final report 1981–84 to ODA Department of Botany, University of Durham, UK.

Owens, J.C., C.R. Ward, E.W. Huddelston and D. Ashdown (1970). 'Nonchemical methods of mosquito control for playa lakes in west Texas', *Mosquito News*, Vol 30, pp 571–579.

Perfect, T.J. (1986). 'Irrigation as a factor influencing the management of agricultural pests', *Philosophical Transactions of the Royal Society of London*, Vol 316, pp 347–354.

Pesigan, T.P., M. Farooq, N.G. Hairston, J.J. Jauregui, E.G. Garcia, A.T. Santos and A.A. Besa (1958). 'Studies on *Schistosoma japonicum* infection in the Philippines. 3. Preliminary control experiments', *Bulletin of the World Health Organization*, Vol 19, pp 223–261.

Petr, T. (1987). 'Food fish as vector control, and strategies for their use in agriculture', pp 87–92 in *Effects of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Rathor, H. (1987). 'Predominant agricultural practices and their bearing on vector-borne disease transmission in the WHO eastern Mediterranean region', pp 44–47 in *Effects of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Reed, D.E., and T.J. Bryant (1972). 'Interaction between water depths and the distribution of *Gambusia affinis* and immature *Culex tarsalis* in Fresno County ricefields', *Proceedings and Papers of the California Mosquito Control Association,* Vol 40, p 122.

Roger, P.A. (1987). 'Effect of algae and aquatic macrophytes on nitrogen dynamics in wetland rice fields', pp 783–793 in *Transactions of the 13th Congress of the International Society of Soil Science*, Hamburg, Germany, 13–21 August, Vol 6.

Roger, P.A., I.F. Grant and P.M. Reddy (1985). *Blue-green Algae in India: A Trip Report*, IRRI, Manila, the Philippines.

Roger, P.A., S.A. Kulasooriya, W.L. Barraquio and I. Watanabe (1981). 'Epiphytic nitrogen fixation on lowland rice plants', pp 62–66 in R. Wetselaar, J.R. Simpson and T. Roswall, eds, *Nitrogen Cycling in Southeast Asian Wet Monsoonal Ecosystems*, Australian Academy of Science, Canberra, Australia.

Roger, P.A., and Y. Kurihara (1988). 'Floodwater biology of tropical wetland ricefields', pp 275–300 in *Proceedings of the First International Symposium on Paddy Soil Fertility*, Chiang Mai, Thailand, 6–13 December.

Roger, P.A., and I. Watanabe (1984). 'Algae and aquatic weeds as a source of organic matter and plant nutrients for wetland rice', pp 147–168 in *Organic Matter and Rice*, IRRI, Manila, the Philippines.

Ruddle, K. (1982). 'Traditional integrated farming systems and rural development: the example of ricefield fisheries in Southeast Asia', *Agricultural Administration*, Vol 10, pp 1–11.

Russell, P.F., F.W. Knipe and H.R. Rao (1942). 'On agricultural malaria and its control with special reference to South India', *Indian Medical Gazette*, Vol 77, pp 744–754.

Saxena, R.C. (1989). 'Insecticides from neem', pp 110–135 in T. Arnason, B.J.R. Philogène and P. Morand, eds, *Insecticides of Plant Origin*, Symposium Series 387, ACS, Washington, DC.

Saxena, R.C., A.V. de Laura and H.D. Justo (1987). 'Golden apple snail: a pest of rice', *International Rice Research Newsletter*, Vol 12, No 1, pp 24–25.

Schaefer, C.H., and M.V. Meisch (1988). 'Integrated mosquito control in small-scale rice production systems', pp 197–201 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Self, L.S. (1987). 'Agricultural practices and their bearing on vector-borne diseases in the WHO western Pacific region', pp 48–56 in *Effects of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Self, L.S., and S.K. De Datta (1988). 'The impact of management practices in rice on mosquito vector propagation', pp 67–84 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Service, M.W. (1975). 'Some predators of Anopheles gambiae larvae in ricefields of Kenya', *Transactions of the Royal Society of Tropical Medicine and Hygiene*, Vol 69, p 181.

Service, M.W. (1977). 'Mortality of immature stages of species B of the *Anopheles gambiae* complex in Kenya: comparison between ricefields and temporary pools, identification of predators, and effects of insecticidal spraying', *Journal of Medical Entomology*, Vol 13, pp 535–544.

Sethunathan, N., and R. Siddaramapa (1978). 'Microbial degradation of pesticides in rice soils', pp 479–497 in *Soils and Rice*, IRRI, Manila, the Philippines.

Sharma, V.P. (1987). 'The green revolution in India and ecological succession of malaria vector', pp 116–124 in *Effects of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Snellen, W.B. (1987). *Malaria Control by Engineering Measures: Pre-World War II Examples from Indonesia*, Reprint No 47, International Land Reclamation Institute, Wageningen, The Netherlands.

Speelman, J.J., and G.M. van den Top (1986). 'Irrigation and vector borne diseases: a case study in Sri Lanka', in *Proceedings of the Workshop on Irrigation and Vector-Borne Disease Transmission*, IIMI, Sri Lanka.

Sugiyama, A., M. Tagaki and K. Maruyama (1985). 'Studies on the variety of predators to *C. tritaeniorhynchus* mosquito larvae in ricefields', *Mie Medical Journal*, Vol 29, pp 385–387 (in Japanese).

Wada, Y. (1974). '*Culex tritaeniorhynchus*', pp 105–118 in R. Pal and R.H. Wharton, eds, *Control of Arthropods of Medical and Veterinary Importance*, Plenum, New York.

Wada, Y. (1988). 'Strategies for control of Japanese encephalitis in rice production systems in developing countries', pp 152–160 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Washino, R.K. (1981). 'Biocontrol of mosquitoes associated with California ricefields with special reference to the recycling of *Lagenidium giganteum* Couch and other microbial agents', pp 122–129 in M. Laird, ed, *Biocontrol of Medical and Veterinary Pests*, Praeger, New York.

Watanabe, M., Y. Wada, K. Itano and S. Suguri (1968). 'Studies on predators of larvae of *Culex tritaeniorhynchus summorusus Dyar*', *Japanese Journal of Sanitary Zoology*, Vol 19, pp 35–38 (in Japanese with an English summary).

Watanabe, I., and P.A. Roger (1985). 'Ecology of flooded ricefields', pp 229–243 in *Wetland Soils: Characterization, Classification, and Utilization*, IRRI, Manila, the Philippines.

Watanabe, I., S.K. De Datta and P.A. Roger (1988). 'Nitrogen cycling in wetland rice soils', pp 239–256 in J.R. Wilson, ed, *Advances in Nitrogen Cycling in Agricultural Ecosystems*, CAB International ed, UK.

Way, M.J. (1987). 'Integrated pest control strategies in food production and their bearing on disease vectors in agricultural lands', pp 107–115 in *Effects of Agricultural Development on Vector-Borne Diseases*, FAO, Rome.

Webbe, G. (1961). 'Breeding sites of malaria vectors in relation to water management and agricultural practice in the Sukumaland area of Tanganyika', *East African Medical Journal*, Vol 38, pp 239–245.

Webbe, G. (1988). 'Planning, design, and operation of rice irrigation schemes: the impact on schistosomiasis', pp 51–65 in *Vector-Borne Disease Control in Humans Through Rice Agroecosystem Management*, IRRI in collaboration with the WHO/FAO/UNEP PEEM, Manila, the Philippines.

Webbe, G., and J.D.H. Lambert (1983). 'Plants that kill snails and prospects for disease control', *Nature*, Vol 302, p 754.

Westerdahl, B.B., R.K. Washino and E.G. Platzer (1982). 'Successful establishment and subsequent recycling of *Romanomermis culicivorax* (Mermithidae: Nematoda) in California ricefields following post parasite application', *Journal of Medical Entomology*, Vol 19, pp 34–41.

WHO (1973). *Epidemiology and Control of Schistosomiasis (Bilharziasis)*, ed N. Ansari, Karger, Basel.

Zebitz, C.P.W. (1986). 'Potential of neem seed kernel extracts in mosquito control', pp 555–573 in H. Schmutterer and K.R.S. Ascher, eds, *Natural Pesticides from the Neem Tree and Other Tropical Plants*, Proceedings of the 3rd International Neem Conference, Nairobi.