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Environmental impacts of wetland rice cultivation

Authors :

ROGER Pierre A
JOULIAN Catherine
 Laboratoire ORSTOM de Microbiologie des Anaerobies (LOMA)
 Université de Provence, CESB/ESIL, Case 925, 163 avenue de Luminy
 - 13288 Marseille Cedex 9 - France
 Tel : + 33 (0)4 91 82 85 71
 Fax: + 33 (0)4 91 82 85 70

Abstract

By the year 2020, the demand for rice will increase by about 50%. Maintaining the sustainability of rice-producing environments requires new concepts and practices. A major concern is the long-term effects of the factors associated with crop intensification-- especially agrochemicals --on soil fertility, the environment, and human health. This review considers major off-field environmental problems related with rice culture :

1. Wetland ricefields and irrigation schemes favour to the propagation of aquatic invertebrates (mosquitoes and snails) vectors of human diseases (malaria, schistosomiasis, and Japanese encephalitis...)
2. Misuse of pesticides has been a major problem associated with new rice technologies, resulting in significant off-field environmental impacts through their effects on non target ricefield fauna, accumulation in the food chain, runoff from the fields, transportation to the water table, and detrimental effects on farmers' health.
3. Ricefields are a major source of CH₄. Crop intensification will increase emission if mitigation techniques adoptable by farmers are not developed.

All these effects are likely to be more marked :

- 1) in tropical and subtropical environments, where climatic and cultural conditions are more favourable to vector-borne diseases and CH₄ production, and,
 - 2) in developing countries where pesticide use is less regulated and pesticide misuse more frequent due to inadequate information of the farmers.
- However negative impacts may also occur in temperate rice growing area.

Policy makers might have difficulties to satisfy the sometimes conflicting concerns for profitable production, food supply, and environmental protection. To help decision, research is still needed on :

- the contribution of ricefields to disease transmission in different environments and the relationships of vectors to cultural practices,
- the conservation of environmental conditions that sustain natural enemies of vectors and rice pests
- the long term effects of pesticides on the rice environment (and soil fertility).
- the effects of various patterns of intermittent drainage on yield, ricefield ecology, and the environmental impacts of rice cultivation, because this practice appears to be usable to simultaneously control vectors and weeds, and reduce CH₄ emission.

Keywords

- Ricefield, environment, human health, vectors, pesticides, methane, greenhouse effect
- Asia, world.

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Introduction

More than half the world's population is dependent upon rice, which occupied 148 million hectares of land in 1991 for a global production of 520 million tons. About 80% of riceland are wetlands where rice grows in flooded fields during all or part of the cropping period. Wetlands account for 93% of world rice production (IRRI).

Modern technologies, which use fertilizers and fertilizer-responsive rice varieties, pesticides, and optimum management practices, have increased yields tremendously. They also have profoundly modified traditional rice-growing environments. It is generally recognized that disturbances of rice growing ecosystem by mechanization and agrochemicals, and the disappearance of permanent reservoirs of organisms in the vicinity of the fields, have decreased species diversity and the number of edible species traditionally harvested from the ricefield (Roger et al 1991). Agrochemical use increases rice yield but

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also, by decreasing species diversity, frequently leads to explosive development of single species that might directly or indirectly have detrimental effects as rice pests, vectors of human diseases, or through their effects on soil fertility (Roger 1995).

By the year 2020, the estimated annual demand for rice will exceed 760 million tons as world population swells to 8 billion persons, more than half of whom will be rice consumers. That production increase of almost 50% will have to be achieved on about the same amount of riceland that is cultivated today. Therefore, maintaining the sustainability of rice-producing environments in the face of increased demands will require new concepts and agricultural practices and a management that should :

- 1) satisfy changing human needs and maintain production over time in the face of ecological difficulties, and social and economic pressure,
- 2) maintain or enhance the quality of the environment, and,
- 3) conserve or enhance natural resources.

Earlier concerns were how to increase yield, optimize agrochemical use, identify and use alternative cheap sources of fertilizer, and, to a lesser extent, preserve the ability of the ricefield to produce additional sources of food. New concerns deal with the sustainability of the rice-growing environment to maintain high yields, and the possible long-term effects of crop intensification and factors associated with it – especially agrochemical use -- on soil fertility, the environment, and human health.

Among environmental problems related with the intensification of rice cultivation, three major aspects have been recognized

- Wetland ricefields and irrigation schemes create ecological conditions favourable to the propagation of aquatic invertebrates that are vectors of human and animal diseases, mostly mosquitoes and snails. The most important vector-borne diseases associated with rice environments are malaria, schistosomiasis, and Japanese encephalitis.
- Misuse of pesticides has been one of the major problems associated with the adoption of new rice technologies, resulting in on-field problems such as increases in pest and plant disease outbreaks, development of pesticide-resistant strains of rice pests (Oka 1988), and significant direct or indirect effects on micro-organisms, primary producers, and floodwater invertebrates important to soil fertility (Roger 1996). Pesticides also have significant off-field environmental impacts through their effects on non target ricefield fauna, their accumulation in components of the food chain, runoff from the fields, transportation to the water table, and detrimental effects on farmers' health.
- Flooding creates anaerobic conditions a few millimetres beneath the soil surface and leads to the production of methane (CH₄), a major greenhouse gas. Ricefields are a major anthropic source of CH₄. Crop intensification will lead to increased CH₄ emission if mitigation techniques adoptable by farmers are not developed.

These three aspects are discussed thereafter.

Table 1. Major vector-borne diseases that may be related to rice cultivation (after Roger and Bhuiyan 1990).

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

Vector borne diseases in rice growing environments

Relation between vector-borne diseases and rice cultivation

Wetland rice culture and irrigation schemes create ecological conditions favourable to the propagation of diseases whose vectors require an aquatic environment, either permanently or at certain stages of their life cycle (Table 1).

Vectors

Major vectors are mosquitoes and aquatic snails. They are ubiquitous in ricefields.

Mosquito reproduction and abundance are affected by plant height, water depth, soil, other environmental conditions, and cultural practices. Their production ranges from about 2 m⁻² per day for *Anopheles* (Hill & Cambournac 1941) to about 20 m⁻² per day for *Culex tritaeniorhynchus* (Heathcote 1970). Larvae populations of up to 3,500 m⁻² were recorded in the Philippines (Simpson et al 1994). Some sun-loving species are found mainly in waters without vegetation, whereas many others prefer the presence of vegetation. Vegetation is necessary for *Mansonia* because both larvae and pupae obtain their O₂ requirements by piercing submerged roots or stems of aquatic macrophytes such as water lettuce (*Pistia*), water hyacinth (*Eichhornia*), or *Salvinia* (Mather & Trinh Ton That 1984). Species succession was observed in ricefields of Burkina Faso (Carnevale & Robert 1987). Heliophilic species, prevalent during early stages of rice growth, were gradually replaced by more shade-loving species when canopy developed. *Anopheles gambiae* developed from flooding to rice booting stage; *A. pharoensis* dominated from booting to heading; it was then replaced by *A. coustani* during the ripening phase.

Aquatic snails are very common in ricefields where they can develop large populations, especially when organic manure is applied. Populations of small-size *Limnea* sp. up to 1,000 m⁻² (1,500 kg ha⁻¹) have been observed in Philippine ricefields (Grant et al 1986). Large species (*Pila* sp., *Pomacea* sp., *Ampullaria* sp.) can develop populations of 1-10 m⁻². Farmers collect them for food or as feed for ducks. Some are detrimental to rice by grazing on seedlings (Saxena et al 1987). *Bilinus* sp., *Biomphalaria* sp., and *Limnea* sp. are vectors of bilharziosis.

Relationships between rice culture and vector-borne diseases

Numerous studies in the tropics have shown the association of wetland rice culture with vector-borne diseases. But the relationships between rice culture and vector-borne diseases are complex and often highly site-specific.

The presence of ricefields and therefore of mosquitoes does not imply that vector-borne diseases will develop. Ricefields in the plains of Assam, India, were found free from the dangerous anophelines (Najera 1988). Sharma (1987) found that, in India, rice cultivation has a very weak relation 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.

The simultaneous occurrence of ricefields and vector-borne diseases in an area does not imply that ricefields are the main source of vectors. Gratz (1988) pointed out that it is difficult to determine how much of anopheline mosquito breeding actually takes place in ricefields. Large ricefields in Malaya were found free of the local vector *Anopheles maculatus* (Muirhead-Thomson 1951). In Burkina Faso, malaria transmission was 2.5 times less intense in the rice-growing villages than in the neighboring villages (Carnevale & 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 extensive seasonal habitats outside the ricefields.

The association of Asian schistosomiasis with rice culture has also been reported (Webbe 1988). It was found that the major breeding grounds of the schistosome snails are the irrigation and drainage ditches, rather than the ricefields per se. Garcia (1988) relates these observations to how recently the snail habitat has been used for rice cultivation and the intensity, continuity, and method of rice culture before the field investigation was conducted. In the Philippines, Garcia (1988) observed that in intensively cultivated rice areas, snails were found 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.

Effect of introducing wetland rice cultivation on vector-borne diseases

Introduction of irrigated rice creates greater mosquito breeding surfaces. At the same time, however, the ecosystem undergoes significant changes that either favour or discourage the ecological niches required for the breeding of certain species. Such changes include duration of flooding, water depth, water turbidity, temperature, and shading pattern. These changes may shift the equilibrium of the indigenous mosquito population and species selection in the area, resulting in a decrease or increase in the transmission potential, depending on which species find the changed ecosystem favourable or unfavourable for breeding. In particular, turning swampy areas into ricefields may reduce vector incidence. Snellen (1987) cited the success of periodic drainage practices to control malaria in Java, Indonesia, during the Dutch colonial time. Agricultural practices were recognized early as modifiers of the malaria risk of an area, and popular wisdom recognized this potential in sayings such as "malaria flees before the plow" (Najera 1988).

There is evidence, however, that the introduction of irrigated rice may increase vector-borne disease incidence. There has been a general mosquito problem, especially proliferation of anophelines, in areas where rice cultivation has been introduced (Carnevale & Robert 1987, Choumkov 1983, Webbe 1961). Rice cultivation tends to increase air humidity, which increases the longevity of mosquitoes. 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, 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.

Effect of crop intensification on vector-borne diseases

There is also evidence that 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 & 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.

Impacts of agrochemicals on vectors

Effects of pesticides

Most agricultural insecticides are non-specific; they are toxic to agricultural pests as well as to some vectors of human diseases. Insecticides have three major effects on vectors:

- 1) they temporarily decrease their incidence,
- 2) they cause resurgence of resistant strains and,
- 3) they adversely affect their natural predators and competitors.

Numerous data in the literature confirm the potential of agricultural insecticides to suppress mosquitoes, larvae as well as adults, and their predators through direct toxicity (Mulla & Lian 1981). Among the probable explanations for the marked reduction of malaria and Japanese encephalitis in Japan since 1945. Self (1987) listed 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 organophosphorus and carbamate insecticides. Self (1987) indicates that in the Republic of Korea, however, pesticide application for agricultural purpose reduced the density of Japanese encephalitis vector *Culex tritaeniorhynchus* in rice-growing areas, but had no effect on the main malaria vector *Anopheles sinensis*. 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 1987, Wada 1974).

In the rice-growing areas in the USA, the elimination of malaria by suppressing the vector with DDT in the post-World War II era led the way for extensive insecticide use against both mosquitoes and agricultural pests. Chlorinated hydrocarbon, organophosphate, carbamate, and 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 adept at evolving resistant strains. A resistant strain arises because some individuals within the population already possess a genetic make-up that confers resistance on them even before their exposure to any insecticide (Mather & 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).

Effects of fertilizers

The blooming of unicellular algae resulting from fertilizer broadcast into the floodwater at the beginning of the crop cycle is generally followed by the proliferation of invertebrates that graze on such algae (ostracods and larvae of chironomids and mosquitoes) (Simpson & Roger 1991, Simpson et al 1994).

Methods of control

The control of vectors of human and animal diseases that develop in ricefields can be achieved, at least partly, by water management, certain agricultural practices, pesticide application, and biological control.

Agricultural practices.

Conventional agricultural practices that affect/control vectors are summarized in Table 2. Among those, the alternate wetting and drying method of water management during the cropping season seems the most promising. It has been recommended to control hemipterous pests such as the brown planthopper *Nilaparvata lugens* (FAO/UNEP 1982) and vectors (Mather & Trinh Ton That 1984, FAO 1987, Lu BaoLin 1988). The method was reported to control efficiently mosquitoes vectors of Japanese encephalitis in large areas in East China while conserving water and increasing yield (Self 1987). It was also reported to reduce aquatic snail incidence (Amerasinghe 1987; Cairncross & Feachem 1983).

The frequency of dry phases must be such that mosquito larvae will dry out before completing immature development (Amerasinghe 1987), a period that can be as short as five days for *Simulium* sp. (Cairncross & Feachem 1983). If submergence water is allowed to dry up, this method requires 30-50% less water than the conventional continuous shallow (5-7 cm) submergence. The saving results mostly from reduced percolation losses. If, however, water from the ricefield is regularly drained off rather than used up to create the dry condition, the total water requirement might exceed that needed for continuous shallow submergence.

To be accepted by farmers, the alternate wetting and drying method must have no negative effect on yield. Reports on this aspect are contradictory. Hill and Cambournac (1941) described a field trial of intermittent irrigation 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 a yield increase (Cairncross & Feachem 1983, Luh Pao-Ling 1984, Self & De Datta 1988), still others show a decrease (IRRI 1987a, IMMI 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, hence benefits from drying are low or nonexistent.

For optimum control, alternate wetting and drying must be practiced simultaneously for all ricefields in a large area, during the entire cultivation season, and under conditions favorable to rapid drying (Amerasinghe 1987). That requires a highly organized system of water application and strict adherence to the designed schedule. Therefore, 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 are drained for vector control (Bhuiyan and Shepard 1987). The method is not efficient to control gastropods that undergo prolonged aestivation and hibernation (Garcia 1988). It also affects nontarget organisms, including aquatic predators.

Importance of system level irrigation management : Water management in the ricefields will be of limited use unless irrigation system management is modified to control vectors that breed outside the ricefields, but within the system's command. Irrigation systems provide breeding habitats of snails and mosquitoes in canals with vegetation; stagnant pools created in depressed areas due to seepage from unlined canals; and dead storage in canals, borrow pits, choked drainage ditches, etc. Parts of the irrigation system outside the ricefields are considered the major breeding grounds of schistosome snails. More farmers probably become infected while washing in irrigation canals than while working in ricefields (Garcia 1988). Most snails feed on vegetation and there is a direct correlation between their populations and the density of aquatic plants; therefore, canals should be free of weeds to prevent explosive growth in snail populations. The weed not only provides food for the snails but an egg-laying surface and cover for the hatchlings (Gaddal 1988).

Table 2. Cultural practices that affect vector populations

METHOD	COMMENTS	REFERENCE(S)
Maintaining soil saturation	Avoiding stagnant water provides vector control. Very difficult to achieve. Requires precise soil leveling and frequent and precise irrigation.	Bhulyan & Shepard 1987
Periodic quick flushing	Remove vector larvae. Very difficult to achieve. Requires well-leveled fields, water control infra-structure for flushing and substantial extra water.	Amerasinghe 1987
Alternate wetting and drying	see in text.	
Wetland-dryland crop rotation	Control snails if water distribution channels and the fields can be dried simultaneously.	Pesigan et al 1958; Webbe 1988
Synchronous planting and harvesting	Disturb the life cycle of rice pests and vectors if performed in large areas. Difficult to achieve in small holding communities.	Perfect 1986 Way 1987
Mechanization and new implements	Plowing before flooding + disking partly control mosquitoes by burying eggs. Use of a rotary hydrotiller reduces populations of large snails.	Cobney et al 1981 Manaligod & Quick in Roger 1996
Direct seeded rice	Earlier closure of the canopy has implications for mosquito breeding that have not been assessed.	Roger & Bhulyan 1990
Pesticides	Most agricultural insecticides and molluscicides are toxic to some vectors (and their predators and competitors). They are primarily applied to control pests. Application to control vectors would be most often perceived as uneconomical.	Simpson & Roger 1995
Weed control	Repeated plowing, harrowing, and weed incorporation render ricefields less suitable for snails and mosquitoes.	Roger & Bhulyan 1990
Azolla, aquatic fern used as green manure	Coverage of the water surface by Azolla inhibit oviposition of Culex sp. But Azolla is a good source of food for snails. Mosquito control is an additional benefit in areas where Azolla is used.	Lu Baolin 1988

Table 3. Managements and agents tested for vector control

METHOD	COMMENTS	REFERENCE(S)
Weed control in irrigation canals and related water bodies	Aquatic weeds = support and food for snails and favorable habitats for some mosquitoes. Control should be performed simultaneously in ricefields and related water bodies.	
Pesticides of plant origin	Considered as cheap. Many are known. Neem (<i>Azadirachta indica</i>) control mosquitoes. Soap-berry (<i>Phytolacca doederleinera</i>) control snails. Potential underexploited in developing countries.	Gaddal 1988 Saxena 1989
Conserving natural predators	Fish feed on mosquito larvae and snails. Aquatic insects and their larvae feed on mosquito larvae. Predators may cause 90% or more mortality of immature mosquitoes. Even if it is not envisioned that invertebrate predators can be exploited as control agents, cultural practices favoring their existence should be encouraged.	Bradley 1986 Washino 1981 Mather & Trinh Ton Thai 1984
Introducing fish predators	Raising fish in ricefields reduced mosquitoes and their larvae by 80 to 90% in rice-growing areas in Henan Province. <i>Gambusia affinis</i> or mosquito fish has been used in the USA for ricefield mosquito control. 750 fish/ha give effective control. Carps can be used for controlling snails. The most promising concept: larvivorous fish that can later be harvested for food.	Pétri 1987 Dame et al 1988 Mochida 1988
Introducing insect predators	Their taxonomy and ecology has to be studied before their possible use can be assessed and methods of multiplying them developed.	Schaefer & Meisch 1988
Nematode predators	<i>Romanomermis culicivorax</i> control mosquitoes. Rearing and pool dispersal refrain its field use.	Kerwin & Washino 1986b
Introducing competitors	The use of competitor snails, <i>Marisa cornuarietis</i> and <i>Tiara</i> to supplant schistosome vector snails, has been successful in ponds and canals.	Gaddal 1988
Microbial agents: <i>Bacillus thuringiensis</i>	The most studied agent. Provide selective control of mosquito larvae, causing little harm to most of the predators of vectors. Used in USA and various countries.	Way 1987 McLaughlin & Vidrine 1984
Microbial agents: others	Bacteria: <i>Bacillus sphaericus</i> Fungi: <i>Gulchomyces</i> , <i>Lagenidium</i> , <i>Toxopneustes</i> , <i>Coelomomyces</i> Viruses: baculoviruses Potential demonstrated but not currently used.	Lacey & Undeen 1986 Kerwin & Washino 1986a; Cowper 1988

A number of methods using various agents have been tested for controlling vectors (Table 3). The potential of biological control has wide appeal to field biologists, but no method is currently used to a noticeable extent and, except possibly for *Bacillus thuringiensis*, no method has yet been sufficiently evaluated to be recommended.

Bacillus thuringiensis serotype H-14 (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 as described in Louisiana, USA, (McLaughlin & Vidrine 1984) is 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 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 liters ha⁻¹.

Among possible methods, the most promising for small farmholders is to stock ricefields with larvivorous fish that could be harvested later for food. Research is needed to identify fish species more suitable to the ricefields than those that now exist in individual country situations. With regard to the potential of food-fish for controlling vectors, it is important to investigate rice cultural practices that are compatible with fish culture. In particular, there is a need to develop pest management technologies, including establishing maximum doses when pesticides are deemed essential, which are compatible with fish culture.

More research on conservation of environmental conditions that sustain natural enemies of vectors is also needed. In many areas, farmers use more pesticides than are required for controlling rice pests. Although natural biological control is not expected to entirely prevent pest damage, neither is the use of pesticides. There is sufficient evidence that destruction of natural populations of predators through overuse of pesticides can lead to the development of undesirable vector species and pesticide resistance.

Conclusion

Floodwater fauna in ricefields can be detrimental by their effects on the rice plant itself or as vectors of human and animal diseases. Their effect as disease vectors is far more important, both sociologically and economically. The control of vectors of human and animal diseases that develop in ricefields can be achieved, at least partly, by water management, agricultural practices such as synchronous planting and harvesting, pesticide application (including botanicals), and biological control. It is highly improbable, however, that rice farmers will adopt measures designed to control vectors only. To be attractive, vector control should be part of cultural practices that increase yield or reduce inputs. Among the possible methods of water management, intermittent irrigation seems promising because of its potential for water saving. The method will also help in reducing methane emission. However, it will also affect natural predators and competitors of the vectors. There is a need to establish the relation to yield of alternate wetting and drying for various soil types and environmental conditions. The cost of water control infrastructure for intermittent irrigation may not be very high, but for sustained success, it will require a level of farmer organization and institutional support not currently available in most tropical rice irrigation systems.

The wide range of plants exhibiting insecticidal or molluscicidal properties offers an alternative for vector control in the tropics, which is underexploited.

The potential of biological control has wide appeal to field biologists, but no method has yet been sufficiently evaluated to warrant its recommendation. Use of competitors was reported to be successful for snail vectors in a few irrigation schemes. It seems that mosquito control by *Bacillus thuringiensis* has had some success in the US; its efficacy and economics should be tested under tropical conditions. A promising method for small farmholders in the tropics is to stock ricefields with larvivorous fish that could later be harvested for food.

Environmental impact of pesticides used in ricefields

The impact of pesticides on ricefields is multifaceted. Their use can cause significant increase in rice yields, but their misuse has been one of the most serious environmental problems associated with the adoption of new rice technologies, resulting in poisonings, environmental contamination, increases in pest and plant disease outbreaks, and in pesticide-resistant strains of rice pests and vectors.

It is recognized that flooded rice soil is an environment favorable for rapid detoxification of many pesticides (Roger and Bhuiyan 1995). However, there are reports of significant direct or indirect effects of pesticides on microorganisms, primary producers, and floodwater invertebrates important to soil fertility (Roger 1995). A major conclusion of recent bibliographic and experimental assessments of pesticides impacts on soil and water microfauna (Roger 1995) and invertebrates (Simpson and Roger 1995) is that current knowledge on wetland soils is too fragmentary to draw conclusions other than general trends. The same apply to pesticide impacts on the rice-growing environment and rice farmers. Pingali (1995) pointed out that the few studies that exist are based on speculative and anecdotal paradigms. A recent multidisciplinary study conducted in the Philippines for two years provide useful information on a case study of pesticide impact on farmer health and the rice environment. However, experimental results, should indeed not be generalized. The book summarizing the results of this study also provide extensive bibliographic analysis on a number of related topics (Pingali and Roger 1995). This section, which is mostly summarized from this book, focus on off-field pesticide impacts on the environment and on impacts on rice farmers and consumers.

Accumulation of pesticides in rice grain

Data from the literature indicate that pesticide residues in rice grain at harvest time were either non detectable or below the tolerance limit set by the United States Food and Drug Administration. Seiber et al (1978) found that residues of carbofuran or its carbamate metabolites in rice plants from fields treated by soil incorporation or root-zone placement, did not exceeded the 0.2 ppm tolerance. Residues above 0.2 ppm were found only in whole grains from plants that received six broadcast application of carbofuran at 14-day intervals throughout the growing season. Del Rosario & Yoshida (1976) recorded low levels of the four BHC isomers in rice seed, plant, and soil samples from five provinces in the Philippines. Levels in the plants were generally higher than in the soil, but were below the tolerance limit. A recent pesticide monitoring in 17 farms in the Philippines for two cropping seasons, showed the absence of detectable levels of all tested pesticides (chlorpyrifos, BPMC, methyl parathion, diazinon, monocrotophos, and endosulfan) in the grain at harvest time (Tejada et al 1995). However, Lee & Ong (1983) reported significant levels of lindane in rice grains collected from warehouse and milling plants. Up to 80 percent of the residues could be removed by repeated washing with water, a practice used before rice is cooked. Boiling further broke down the residues. Lindane was present in only trace amounts in farmers' rice although the chemical had been used in ricefields.

Post harvest treatments seems to bring higher concentration of pesticides in grain than field application. The presence of DDT and its metabolites in grain samples in the Philippines was attributed to the contamination from the DDT sprayed for malaria control in the dwelling places where the rice was stored (Del Rosario & Yoshida 1976). Monitoring studies of stored grains in 18 National Grain Authorities warehouses of the Philippines showed that post-harvest treatment resulted in significant amounts of residues that were however within the limit set by the FAO/WHO for grains (Pingali 1995).

Accumulation in organisms collected as food from ricefields

Crop intensification has reduced the number of edible species traditionally harvested from the ricefield. Heckman (1979) reported that, in northern Thailand, one vegetable and 16 edible animals (snail, shrimp, crab, large water bug, fish, and frog) were collected in a single ricefield within one year. Such a diversity of food harvested from ricefields is now uncommon (Roger 1996), but a number of species, (mostly *Ipomea aquatica*, fish, frogs, and snails) are still collected as food in many tropical ricefields. In the Philippines 34 % of the farmers the Laguna area (where pesticide use is average) and 63% of those of Nueva Ecija area (where pesticide use is high) get food other than rice from the ricefield ecosystem. Surprisingly farmers with a high intensity of pesticide use were collecting as much food out of the fields as farmers with low levels of pesticide use (Warbuton et al 1995).

The impact of pesticides on the ricefield vertebrates can summarized as follows :

- 1) the absolute number of aquatic vertebrates declines rapidly with pesticide use, with mortality usually occurring within the first five to seven days after pesticide application ; and,
- 2) for the surviving populations, the level of detectable residues was generally small (Pingali 1995).

Tejada et al (1995) examined pesticide residues in aquatic organisms and animals found within rice farms in Laguna area (Philippines) forty-five days after transplanting, when the fields had been exposed to one herbicide and at least one insecticide application. Pesticides used in the area were : BPMC, Butachlor, Carbofuran, Chlorpyrifos, Chlorpyrifos, Decamethrin, Endosulfan, Fentin sulfate, Fenvalerate, Isoprocarb, Methyl parathion, MIPC, Monocrotophos, and Niclosamine. In the wet season, all aquatic animals revealed the possible presence of Isoprocarb. This, was attributed to the low solubility and long half-life of Isoprocarb. In the dry season, levels of Monocrotophos and Chlorpyrifos ranging from traces to 0.140 mg kg⁻¹ were recorded in frogs and ducks and chickens living on the farm. Concentrations recorded were below the FAO/WHO acceptable daily intake level.

Cagauan (1995) reviewed data on bio-accumulation in fish of common rice pesticides used at recommended doses. Fish that survive the first week of insecticide application rarely contained pesticide residues if recommended rates of organophosphates, carbamates and synthetic pyrethroids were used. Organo-chlorine compounds can accumulate in fish because they are relatively more persistent. The impact on fish of pesticides currently recommended for rice is their direct toxicity leading to high mortality rather than their bio-accumulation. Pesticide bio-accumulation in harvestable and edible size fish would be observed only in cases where low toxic but persistent chemicals are repeatedly applied.

Table 4. Health impairments among rice farmers from areas with different pesticide use intensity in the Philippines (adapted from Pingali et al 1995)

Rice growing area Pesticide use Number of farmers examined	% of farmers with health impairments		
	Quezon none	Laguna average	Nueva Ecija high
Effect Parameters (health indicators)			
Eye (pterygium)	10 a	25 b	67 c
Dermatologic system (nail pitting, eczema)	0 a	14 b	46 c
Respiratory system (Bronchial asthma, abnormal PE findings)	23 a	48 b	46 b
Cardiovascular system (elevated BP, EKG)	46 a	50 a	49 a
Gastrointestinal tract (chronic gastritis)	0 a	57 b	9 a
Polynuropathy	0 a	5 ab	11 b
Number of positive health index	% of farmers:		
0	5	2	0
1	40	7	5
2	33	12	12
3	18	34	28
4	4	25	32
5		20	14
6		0	5
7		0	4

Impacts on farmers

Prolonged exposure to pesticides can lead to cardiopulmonary disorders, neurological and hematological symptoms and skin diseases. Medical comparisons of Filipino farmers exposed to pesticides with unexposed farmers revealed that the exposed groups faced significantly higher acute and chronic health effects (Pingali et al 1995). Pesticides linked with these impairments included certain organo-phosphates, organochlorines, organotin, and phenoxy herbicides. Farmers using the highly hazardous category I and II chemicals were more susceptible to pesticide-related health impairments than farmers using the relatively less hazardous category III and IV chemicals. Pesticide use has a significant positive association with the incidence of multiple health impairments (Table 4).

Pingali et al (1995) computed costs faced by farmers due to health based on the medical tests conducted. Treatment costs (including medication and physicians' fees) plus the opportunity cost of farmers' time lost in recuperation formed a measure of the health cost per farmer. The average health cost for farmers exposed to pesticides was approximately 40 % higher than that for the unexposed farmers. Even after accounting for age, nutritional status, smoking, and drinking, health costs increase by 0.5 percent for every 1 percent increase in insecticide dose above the average level. The loss in labor productivity associated with impaired health was not taken into account in this calculation.

Negative impacts of pesticides on Filipino farmer health was for a significant part due to improper pesticide use practices (Warburton et al 1995). Those included improper storage and disposal practices (65 to 87% of the farmers), improper protection when applying pesticides (95 % wear only partial protective clothing), too short reentry periods (72 to 75 % of the farmers). Ironically, in a parallel study, Heong et al (1995) concluded that among 841 insecticide sprays only 190 (23%) could be considered to be applied at the appropriate time for the intended targets. Out of this, only 160 (19%) used a chemical that could affect the intended pest and in some way prevented yield loss. About 78% of the farmers applied their first spray in the first 30 days after transplanting, at a time were it was not only wasteful but damaging to the predator-pray balance and could lead to secondary pest outbreak.

Impacts on the environment

The environmental pollution from pesticides is caused mainly by the physical processes of pesticide transfer. Several of these processes may be active simultaneously. Soil is contaminated by pesticides adsorption, surface water is contaminated by pesticides moved through runoff, groundwater quality is deteriorated by pesticides reaching the water table through leaching and deep percolation, and the atmosphere is polluted by drifts and volatilization of pesticides.

Drifts

In most rice growing countries, pesticides are applied by backpack and drifts are limited to the vicinity of the field. When pesticides are applied by plane on a larger scale drifts are more likely to occur. Damage to other sensitive crops due to drifts of phenoxy herbicides and propanil have occurred in US rice areas. As a result, regulatory agencies in the US rice states restrict the use of aerial and ground application of herbicides. In Arkansas, phenoxy herbicides cannot be applied within 6 km of cotton (Hill & Hawkins 1996).

Surface water bodies

Pesticides applied on ricefields enter surface water bodies mainly through runoff. Accumulation of pesticide residues in surface waters bodies can have far-reaching consequences for domestic water supply and aquatic organisms. Pesticide contamination of surface water bodies can be assessed by monitoring residues in aquatic food webs.

In the 70's fish kills were attributed to pesticides applied in ricefields in US. Aldrin applied with seed rice entered the aquatic ecosystem through drainage of flooded ricefields-marshland ecosystem. Residue analysis of representative species of the aquatic biota indicated significant biological accumulation; rapid

concentration of pesticides in living organisms resulted in a massive kill of aquatic organisms (Ginn & Fisher 1974). Herbicides used in ricefields have caused problems in the Sacramento River, California and restrictions have been imposed on their use to prevent or reduce contamination. The problem herbicides are thiobencarb which gives a bitter taste to water and molinate which is toxic to fish. Water must be retained on the farm for 14 and 12 days after use of thiobencarb and molinate, respectively, to keep the concentration of thiobencarb in the river below 8 ppb and that of molinate below 4.5 ppb (Moody 1990).

Ground water system

Groundwater contamination by agricultural chemicals is a major environmental pollution issue. In recent years, a number of organic contaminants have been detected in groundwater samples. In the US, 17 different pesticides have been detected in groundwater in 23 different states; the concentrations typically ranged from trace amounts to several hundred parts per billion (Sun 1986). In California, rice herbicides residues have been found in well waters, agricultural drains, and rivers (Cornacchia et al 1984). Water samples from 46 wells the Philippines situated near (6 to 200 m) the rice fields with depth ranging from 10 to 20 m were analyzed for pesticides (Bhuiyan & Castañeda 1995). In this area well water is used as drinking water by most farmers. Insecticides and herbicides commonly applied by farmers in the Laguna area (where pesticide use is average) were detected in most of the water samples, with highest frequencies of occurrence during the wet season (endosulfan 98%; butachlor 76%, methyl parathion 50%). Residue analysis also detected chemicals that were not reported to be applied by farmers during the year (lindane 74%; diazinon 45, % DDT 32%...). Results showed seasonal concentrations of these chemicals that individually did not exceed maximum acceptable daily intake (ADI) levels but that were close to maximum ADI when analyzed pesticides were considered all together. It was clear that multiple toxicity should be a major concern. A small but significant amount of pesticides leaching into the groundwater was also detected.

A study of the dynamics of endosulfan and monocrotophos showed that :

- (1) these chemicals degrade within two weeks in the paddy water and in the top soil (up to 25 cm depth) due to active microbiological and chemical degradation,
- (2) significant amounts of these chemicals were found at the 25 to 125 cm depth, and up to 35 days after spraying and,
- (3) detectable amounts were found at 175 cm depth at 73 days after application (Tejada et al 1995).

These results indicate the possible threat of shallow groundwater contamination from the intensive use of pesticides.

Groundwater contamination possibility is higher in rice-growing areas where intensive rice production has been in practice for many years and pesticide use is common, the most vulnerable being the areas with shallow groundwater table overlain with light-textured aquifers from where shallow lifting of groundwater is made for domestic use (Bhuiyan & Castañeda 1995).

Conclusions

Careful measurement and documentation of the environmental and human health consequences of pesticide use is rare for developing country agriculture. The study in the Philippines evidenced that indiscriminate use of pesticide, especially insecticides, can have serious environmental and human health consequences. Long term effects are still not assessed. On the short term, the major negative impact of pesticides is on farmers health. Explicitly accounting for health costs substantially raise the cost of using pesticides. The economic synthesis for insecticide use in the Philippines (Pingali et al 1995) demonstrated that the value of crop lost to pests is invariably lower than the cost of treating pesticide-caused diseases. In addition productivity benefits of pesticide use appears to be questionable. Whereas pesticides are supposed to be a risk-reducing input, Rola & Pingali (1993) provided empirical evidence that shows that insecticide application increases rice yield variability. Pingali & Rola (1995) concluded that when health costs are considered, the natural control (not applying insecticide) option is the most profitable and useful strategy for insect pest control. Antle and Pingali (1994) provided simulation showing that taxing hazardous insecticides has significant positive farmer health benefits, which leads to an increased in productivity. The same argument does not hold for herbicides because (1) herbicides are generally less toxic chemicals, therefore the health benefits are smaller and (2) the yield response to herbicides is substantially higher than the response to insecticide. Technological alternatives to insecticides exist. According to Pingali and Rola (1995), the development of host plant resistance and integrated pest management (IPM) strategies would strongly minimize insecticide use in the long term. However IPM in the tropics encounters limitations mostly due to the lack of research and extension personnel and facilities.

Increasing labor cost in Asia is favoring a change from transplanted to direct-seeded rice. As this occur, weed problems are expected to increase. Asian farmers will need cultural practices and herbicides with more selectivity than those that are effective in transplanted rice. Temperate rice countries have already faced the environmental problems resulting from intensive herbicide use. Hill and Hawkins (1996) analyzed the situation in US and compared it with what can be expected in Asia as summarized thereafter. In US, a number of rice herbicide registrations have been cancelled for a variety of toxicological and environmental problems. As a result only five herbicides (bensulfuron, molinate, thiobencarb, propanil and the phenoxy herbicides) are currently available in California and two of them have severe hecterage restrictions. This has discouraged private sector to develop new herbicides for US rice. As a result, US rice farmers continue to integrate preventive and cultural practices with chemical weed control. These practices include weed-free seed, crop rotation, land levelling, cultivation, water management, and fertilizer management. However it has been shown that without herbicides yields cannot be maintained at the high levels now possible. In US, where food supplies are plentiful and incomes relatively high, a regulatory agriculture has less impact on food availability than it does in tropical countries where food is scarce. Pesticide regulation in tropical countries can be expected to be less than in US, given the governmental focus on securing adequate food supply. The expected increase in herbicide use should however be coupled with appropriate regulations, perhaps standardized across countries so that cost of registration could be shared, to protect human health and environmental quality. Training and monitoring will be needed to ensure this safeguard.

Emission of greenhouse gases by ricefields

Because of increasing anthropogenic activities, methane (CH₄) concentration in the atmosphere has increased annually by about 1.0 to 0.8% during the last decades (Steele et al 1992). The effect of this increase on global warming is highly significant because CH₄ has a high potential for absorbing infrared radiation, up to 32 times that of carbon dioxide (Blake & Rowland 1988). The possible detrimental effects of global warming have been widely presented in scientific reviews (Zepp 1994) and popularisation articles.

Contribution of wetland rice to global methane emissions

The total annual global emission of CH₄ is estimated to be 410-600 x 10¹² g CH₄ yr⁻¹ (IPCC 1994), 70 to 80% of which is of biogenic origin (Bouwman 1990). Methane emission from wetland rice agriculture have been estimated up to 100 Tg yr⁻¹ which account for approximately 20% of the global anthropogenic CH₄ budget. According to IPCC (1994), flooded rice fields are one of the two the main agricultural source of CH₄, together with ruminant enteric digestion (up to 100 Tg yr⁻¹). The growing demand for rice is most likely to be met by the existing cultivated wetland rice area through intensifying rice production in all rice ecologies, mainly in irrigated and rainfed rice. Coupled with existing rice production technologies, global CH₄ emissions from wetland rice agriculture are likely to increase. Mitigation of CH₄ emissions are needed to stabilize or even lower atmospheric concentrations.

Methane emission by ricefields

Methane emission from ricefields results from :

- 1) its production by methanogenic bacteria in reduced soil,
- 2) its consumption by methanotrophic bacteria in the oxic zones of the ecosystem (submersion water, water/soil interface, rice rhizosphere—including the inner part of the roots—, and culms) where up to 90% of CH₄ produced is reoxidized (Conrad & Rothfuss 1991, Bender & Conrad 1992), and
- 3) transfer processes (diffusion, ebullition) through the soil and the rice plant (Schütz et al 1989b). At the beginning of the crop cycle, ebullition is the main way of transfer of CH₄ to the atmosphere. When plants develop, diffusion through rice plant aerenchyma becomes the main way allowing the transfer of more than 90% of CH₄ emitted during the reproductive phase of rice (Cicerone & Shetter 1981, Schütz et al 1989b).

Microflora involved in methane emission

The presence of methanogenic and methanotrophic bacteria in rice soils was indirectly demonstrated by measurements of CH₄ production and oxidation (De Bont et al 1978, Schütz et al 1989b), but the microflora involved is still imperfectly known. Quantitative data are still scarce and only four genera of methanogens and two genera of methanotrophs have been isolated from rice soils.

A number of data seems to indicate that populations of methanogen do not exhibit large variations during the crop cycle (Schütz et al 1989b, Mayer & Conrad 1990) and the dry fallow that follows rice harvest (Joulian et al 1996). Methanogenesis is probably more limited by substrate availability than by the density of methanogens.

Spore-forming methanotrophs (Type II) are probably dominant in ricefields (Le Mer et al 1996). Escoffier et al (1997) reported increases in methanotroph population by up to 105 times in dry ricefield soils preincubated under CH₄, showing the strong inductive power of CH₄ on these populations and providing an indirect estimate of their high potential in oxidizing CH₄ produced in waterlogged ricefields. The inductive power of CH₄ on methanotrophs in ricefields was also reported by Bender & Conrad (1992) and Watanabe I. et al (1995). As compared with soil, methanotrophs are more abundant in the rhizosphere (De Bont et al 1978) where their abundance increase with rice growth (Gilbert & Frenzel 1995).

Joulian et al (in press) reported that methanotrophs were 4 to 104 times more abundant than methanogens in most of the 22 ricefield soils studied and that the duration of the dry fallow seems to increase the methanotrophs/methanogens ratio.

Estimations of methane emissions by ricefields

A wide range of emissions has been reported with daily values from <0.01 to 1.44 g CH₄ m⁻² day⁻¹ and seasonal estimate from <1 to 173 g CH₄ m⁻² per crop cycle. Highest values (13 to 173 g m⁻² CH₄ per crop cycle) were reported for China (Sass 1994) where green manures have been intensively used.

Dynamics during the crop cycle

CH₄ emission varies with cultural practices and mostly depends upon soil Eh and substrate availability. Several dynamics were reported (Wang et al 1994, Yagi et al 1994, Neue et al 1994, Sass & Fisher 1994). A first peak, may be observed shortly after soil submersion and is attributed to the availability of easily mineralizable organic matter (OM). It is usually observed only in fields where organic manure was applied (Neue et al 1994, Watanabe A. et al 1995). A second peak develops during the vegetative phase of rice and may results from an increased exudation of carbon substrates in rice rhizosphere. A third peak, observed at the end of the crop cycle, might results from increased production of carbon substrates in rice rhizosphere in relation with plant senescence. However a broad range of variations has been reported, especially for the peak(s) occurring during the middle part of the crop cycle (see Minami et al 1994). A last peak is usually observed after harvest when drying up of the soil lead to the formation of cracks through which soil entrapped CH₄ escapes. This peak correspond to approximately 10% of the CH₄ emitted during the crop cycle (Denier van der Gon et al 1996).

CH₄ emission exhibit variations correlated with daily changes in temperature (Schütz et al 1990, Sass & Fisher 1994). Peaks of emission at night were attributed to a lower methanotrophic activity due to the lower oxygen availability (Wang et al 1994) resulting itself from the absence of photosynthetic activity by the plant and the photosynthetic aquatic biomass (Roger 1996).

Factors influencing methane emission from ricefields

Soil properties

One could expect clay soils, poorly drained, and prone to anaerobiosis, to be favourable to methanogenesis. However, using data of Garcia et al (1974) and Neue et al (1994), Joulian et al (in press) found a negative correlation between soil methanogenic potential and soil clay content. Apparently some clay types protect organic matter from mineralization (Oades 1988), which slow down methanogenesis. Soils rich in lattice clays appears to be more favourable to methanogenesis than sandy or loamy soils and soils rich kaolinites in which submersion increases apparent density and slow down changes in soil pH and Eh and OM decomposition (Neue et al 1990, Sass et al 1991). A high clay content may also increase CH₄ entrapping, thus reducing emission (Sass & Fisher 1994).

Methanogens are mostly neutrophilic (Garcia 1990). Therefore, CH₄ production is favoured by a neutral or slightly alkaline soil pH and is sensitive to pH variations (Wang et al 1993). CH₄ production seems to be higher in calcareous soils (Denier van der Gon 1996), possibly because of a buffering effect of carbonates (Neue & Roger 1994). A positive correlation may be observed between the methanogenic potential of rice soils and their OM content, however it should not be considered as a rule (Joulian et al in press), as salinity (Garcia et al 1974) or other factors may limit methanogenesis. Low soil temperature decreases CH₄ production by reducing methanogens activity — which is optimum between 30 and 40°C — but also that of other bacteria involved in methanogenic fermentation, which appears to be even more sensitive to temperature than methanogens (Conrad et al 1987).

From the study of 22 rice soils, Joulian et al (in press) concluded that soils prone to methanotrophy were above neutrality, rich in available P and with lower clay content. On the other hand OM content did not had a significant effect of on populations of methanotrophs and their activity.

Agricultural practices

Water management is a key factor in CH₄ emission. Soil submersion, by decreasing oxygen availability in the bulk of soil, allow the development of the reduced conditions needed for methanogenesis. Soil drainage during the crop cycle may allow some reoxydation, reduce methanogenesis and favour methanotrophy. Several experiments confirm a significant impact of intermittent drainage in reducing CH₄ emission (Sass et al 1992, Watanabe A. et al 1995, Neue et al 1996) (see thereafter). Water regime during fallow also affects CH₄ emission during the crop cycle. In a pot experiment, CH₄ emission was reduced during the entire rice growing season if the soil was kept dry during the fallow (Trolldenier 1995).

Organic matter incorporation is known to enhance CH₄ emission, as shown by field studies. The emission decreases with the C/N ratio of the OM. Incorporating 5 to 12 t ha⁻¹ of straw (C/N ± 60) increased CH₄ emission by 2 to 9 times (Schütz et al 1989a, Sass et al 1991, Yagi & Minami 1990).

Wassmann et al 1996). Incorporating 11 to 31 t of green manure (*Sesbania*) (C/N \pm 30) increased CH₄ emission by 2 to 5 times (Denier van der Gon & Neue 1995). Incorporating 12 t ha⁻¹ of straw compost (C/N \pm 15-20) did even not doubled CH₄ emission (Yagi & Minami 1990).

Mineral fertilizers have complex effects on CH₄ emission that sometimes appears to be contradictory. They varies with the nature and the quantity of the chemical fertilizer and the method of application. Nitrogen fertilizers affect both methanogens and methanotrophs.

Because of the competition between sulfate-reducing bacteria and methanogens, sulfate-containing fertilizers (Schütz et al 1989a) and gypsum, usually applied to reclaim sodic or alkaline soils, (Denier van der Gon & Neue 1994, Lindau et al 1994) reduce CH₄ emission. Ammonium containing fertilizers may also reduce methanogenesis when nitrified, as nitrates are inhibitory to methanogenesis (Conrad & Rothfuss 1991, Jugsujinda et al 1995).

In a pot experiment, CH₄ emission was the lowest when ammonium sulfate was applied, followed by ammonium chloride and urea (Kimura et al 1992). In situ application of ammonium sulfate or potassium nitrate reduced CH₄ emission by more than 50% as compared to the same N rate applied as urea (Lindau 1994). The same study showed that CH₄ emission was more reduced by the application of 120 kg N ha⁻¹ than by 60 kg N ha⁻¹ both in the form of ammonium sulfate or potassium nitrate. Schütz et al (1989a) reported that ammonium sulfate incorporated into the soil reduced more CH₄ emission (60%) than when surface applied. Similarly, CH₄ emission was reduced by 40% when urea (100-200 kg N ha⁻¹) was incorporated into the soil, as compared with an unfertilized plot, while it increased by 20% when urea was surface applied. However, 140 kg N ha⁻¹ ammonium sulfate increased by five times of CH₄ emission in a Californian ricefield (Cicerone & Shetter 1981).

An inhibitory effect of ammonium on methanotrophy, lasting for several months, was reported by Mancinelli (1995) in oxic soils. A similar effect was reported in vitro at the soil-water interface of a submerged ricefield soil, but failed to be confirmed in situ (Conrad & Rothfuss 1991). A higher CH₄ emission when urea was surface applied (Schütz et al 1989a) may partly have resulted from methanotroph inhibition.

Possible methods of mitigation of methane emission

Joulian et al (in press) reported that the potential for methanotrophy was higher than that for methanogenesis in most rice soils. This indicates that all CH₄ produced in a ricefield can theoretically be reoxidized. CH₄ emission from ricefields can be reduced by :

1. temporary drainage periods during the crop cycle,
2. using mineral fertilizers rather than organic, and possibly
3. using selected rice varieties.

Water management

Field drainage during the crop cycle clearly reduces CH₄ emission from ricefields (Sass et al 1992, Watanabe A. et al 1995, Neue et al 1996) and is probably the most easily adoptable method by farmers, indeed not for their current interest in reducing CH₄ emission, but for other possible advantages.

Field drainage during the crop cycle is already practiced on direct seeded rice to allow a stronger establishment of rice seedlings. Short field drainage at tillering may also favour rice growth (De Datta 1981). It also favours nitrogen mineralization and reduces soil toxicity. It has been traditionally practiced in Japan (Sass et al 1992) to prevent hydrogen sulphide toxicity in rice rhizosphere, a disorder known as Akiochi. It also helps controlling vector populations (see above).

Field drainage during the crop cycle may however affect rice growth. Irrigated rice is more sensitive to water stress during flowering and maturation (De Datta 1981). Effects on yields are discussed in the section on vectors. Variable effects were also reported in fields where CH₄ emission was measured. Intermittent drainage reduced CH₄ emission in a Texas ricefield by 50% with a 6-days mid-season aeration, and by more than 80% with a multiple aeration (2-3 days), without reducing rice yield. In contrast, a late flood (76 days after planting) enhanced CH₄ emission and reduced rice yield (Sass et al 1992). In Japan, a 4-days drainage at flowering reduced CH₄ emission without affecting rice growth (Watanabe A. et al 1995).

Field drainage during the crop cycle has also some other disadvantages. It may enhance nitrification and denitrification, so increasing nitrogen losses and also the emission of N₂O (greenhouse gas). Water requirement may be higher if water is drained instead of allowed to dry up (Sass et al 1992).

Other water management practices, such as increasing water percolation or keeping soil saturated instead of flooded, may reduced CH₄ emission, but impacts on CH₄ emission and rice yield need to be tested in situ (Wassmann et al 1993).

Fertilization

It is clear that avoiding/reducing organic fertilizer use will reduce CH₄ emission. However, organic matter input as straw, manure, or green manure has been long advocated in rice cultivation to reduce chemical input and maintain soil long-term fertility. Among chemical fertilizers, those containing sulfate seems to be the most efficient in reducing methane emission but sulfate may also be detrimental to rice by favoring sulfate-reduction in the spermosphere and the rhizosphere of the young plants (De Datta 1981). As available P seems to be a key factor for methanotrophy, P application might reduce emission but field studies are needed to confirm this hypothesis.

Rice varieties

Rice plant plays a major role in CH₄ emission, (1) as a duct allowing the transfer of CH₄ to the atmosphere and O₂ to the rhizosphere, and (2) as a carbon source for methanogens. Planted ricefields emit more CH₄ than wet fallow fields (Schütz et al 1989a).

Traditionally rice selection has been oriented toward productive plants with a high grain/straw ratio, able to utilize soil N. and resistant to pests and diseases. Recent prospective selection was oriented toward varieties with an aerenchyma that limit CH₄ transfer. Watanabe A. et al (1995) demonstrated varietal differences in CH₄ emission but failed in correlating it with the number and size of tillers, and plant biomass or root biomass. A new variety (IR65597) developed by IIRRI emit about 30% less CH₄ than traditional variety « Dular » whose stem and root system are more developed (Neue et al 1996).

Taking into account the quantity (Ladha et al 1986) and quality (Kludze et al 1995) of root exudates, the size and the oxidative power of the root system, which depend upon rice varieties, it might be possible to select plants with a lower potential for CH₄ production/emission. However varieties with a small root biomass will be less favourable for extracting nutrients from the soil and for biological N₂ fixation.

Conclusion

Rice fields are a major source of methane which significantly contribute to global warming. Methane emission is currently not a concern for most rice

farmers, however, with regard to the foreseeable intensification of rice culture, methane emission from ricefield is a concern for the scientific community.

Introducing drainage periods during the crop cycle appears to be the most promising management to favour methanotrophy and reduce methanogenesis, thus reducing CH₄ emission. Under well defined conditions, such a practice may have other advantageous effects such as favoring rice growth, saving on water, and controlling some rice pests and disease vectors (Roger, 1996). This might help in its adoption. Fertilizer management (organic vs. chemical) will highly depend upon the socio-economic environment and recommendations on OM incorporation should find the right balance between promoting long-term soil fertility and maintaining low CH₄ emission. Varietal selection oriented toward low methane emission is still at the research level; it would certainly be most adoptable method of reducing CH₄ emission.

General conclusion

Rice culture has definitely negative impacts on the environment outside of the ricefields and on farmer health, by providing a reservoir of vectors of human diseases and through undesirable effects of pesticides. Rice culture is also a major anthropic source of CH₄, responsible for global warming as a greenhouse gas.

All these effects are likely to be more marked

- (1) in tropical and subtropical environments where climatic and cultural conditions are more favourable for vector-borne diseases and methane production, and,
- (2) in developing countries where pesticide use is less regulated and pesticide misuse more frequent due to insufficient or even erroneous information of the farmers.

However negative impacts of rice cultivation are also likely to occur in temperate rice growing area. Whereas vector-borne diseases are not frequent in these regions, mosquito constitute a recognized nuisance and are still a potential danger as vectors. Recently, media have reported dramatic mosquito pullulation in rice growing area of Italy. Even if pesticide regulations are well developed in most temperate rice growing countries, there are enough recent examples of pollution by agrochemicals to justify regular monitoring of pesticide residues, as practiced in US.

The contribution of rice cultivation to global warming is demonstrated but is currently not a concern for rice farmers.

Policy makers might have difficulties to satisfy simultaneously the sometimes conflicting concerns for profitable production, sufficient food supply, and environmental protection. In the case of vectors of human diseases and detrimental effects of pesticides, the interest of farmers, the economics at country level, and the environmental concern are not divergent. If apparent conflicting situations occurs this might be most often due to an inadequate farmers' perception resulting itself from an inadequate of insufficient information.

Conflicting situations may occur, when regulations becomes too restricting for farmers, as reported for herbicide use in US or even when recommended practices cannot satisfy simultaneous requirements. Thereafter are two examples. Organic fertilizer, including N₂-fixing green manures, have been advocated by research organizations in most rice growing countries for the last decades, emphasizing the long terms effect on soil fertility and sustainability of rice production. On the other hand, organic manuring is now known to favours CH₄ emission. Environmental concern has lead to regulations limiting rice straw burning and promoting its incorporation. Straw incorporation is known to favour long term soil fertility. On the other hand it may :

- 1) favour the persistence of rice pathogens and lead to an increased use of phytosanitary chemicals, and
- 2) cause the production within one year of a quantity of methane equivalent to about 50% of the CO₂ that would have been produced by burning. Knowing that up to 90% of the methane produced is reoxidized and the CH₄ is about 32 times more efficient than CO₂ as greenhouse gas, the final balance is an increase by about 50% of the infrared absorption potential of greenhouse gases produced.

Without trying to be exhaustive, a number of research needs is presented thereafter :

1. Concern about vector-borne diseases is not recent, but quantitative data on the contribution of ricefields to their transmission in different environments are limited. As a result, many speculative conclusions have appeared in the literature. Given the severity and extent 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 relationships of vectors to various rice cultural practices is needed.
2. More research on conservation of environmental conditions that sustain natural enemies of vectors and rice pests is needed.
3. Study of the effects of pesticides, hitherto mostly restricted to short-term laboratory conditions, must be performed under more realistic field conditions and cultural practices. In particular, pesticides effects absolutely need to be assessed on a long term basis. This is needed for environmental impacts but also primarily for possible effects on long term soil fertility.
4. Intermittent drainage is a practice that appears to be usable to simultaneously control vectors and weeds, and to reduce methane emission. It might have beneficial or detrimental effects on rice. More research is needed to simultaneously assess the effects of various patterns of intermittent drainage on yield, ricefield ecology, and the environmental impacts of rice cultivation.

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