Vector-borne Disease Control in Humans Through Rice Agroecosystem Management

International Rice Research Institute

WHO/FAO/UNEP Panel of Experts on
Environmental Management for Vector Control

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Proceedings of the Workshop on
Research and Training Needs in the Field
of integrated Vector-borne Disease Control
in Riceland Agroecosystems of Developing Countries
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The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of the 13 nonprofit international research and training centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is sponsored by the Food and Agriculture Organization (FAO) of the United Nations, the International Bank for Reconstruction and Development (World Bank), and the United Nations Development Programme (UNDP). The CGIAR consists of 50 donor countries, international and regional organizations, and private foundations.

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The World Health Organization, the Food and Agriculture Organization of the United Nations, and the United Nations Environment Programme established the WHO/FAO/UNEP Panel of Experts on Environmental Management for Vector Control (PEEM) in 1981. The objective of PEEM is to create an institutional framework for interagency and intersectoral collaboration by bringing together various organizations and institutions involved in health, water and land development, and the protection of the environment. PEEM promotes the extended use of environmental management measures for vector control in health and development programs.

The responsibility for this publication rests with the International Rice Research Institute.

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Foreword

Vector-borne diseases adversely affect the health and quality of life of millions of people in the tropics and subtropics. Riceland agroecosystems, in which water is present on the land throughout much of the crop growing season, may provide ideal habitats for mosquito vectors that transmit some diseases directly and for snails that act as intermediate hosts for other diseases.

What are the relations between riceland agroecosystems, disease vectors, and the human and domestic animal populations? Why are vector-borne diseases relatively rare in some well-established irrigation systems and endemic in other newer systems? Are vector-borne diseases a necessary consequence of agricultural development, particularly in the ricefield agroecosystem? Must we choose between agricultural development and human health, or can we have both?

Questions such as those were the impetus for the *Workshop on Research and Training Needs in the Field of Integrated Vector-borne Disease Control in Riceland Agroecosystems of Developing Countries* held 9-14 March 1987 at the International Rice Research Institute (IRRI), at Los Baños, Philippines. For the first time, health professionals, medical entomologists, irrigation specialists, and agronomists approached these questions, not within the isolation of their own disciplines, but as part of the complex riceland agroecosystem.

The Workshop recommendations provide a cohesive framework for collaborative research on integrated vector and riceland management and for training. Emphasis remains on sustainable high yields in the face of continuing population pressures. But rice scientists are increasingly concerned with rice cultural practices that can help to control disease vectors, and public health personnel are showing more interest in assessing their vector control measures against the requirements of the rice crop.

I am grateful to our cosponsors—the Panel of Experts on Environmental Management for Vector Control (PEEM), which is supported by the World Health Organization, the Food and Agriculture Organization of the United Nations, and the United Nations Environment Programme; and the United States Department of Agriculture Riceland Mosquito Management Program.

Special thanks are due the organizing committee, which so successfully brought together a diverse, but not necessarily divergent, group of scientists: B. Cariaso, University of the Philippines at Los Baños; E. J. Garcia, Philippine Department of Health; S. I. Julian, National Irrigation Administration, Philippines; L. S. Self, WHO, Manila; and S. I. Bhuiyan, D. J. Greenland, T. R. Hargrove, and B. M. Shepard, all from IRRI.

This book was edited by W. H. Smith, assisted by E. P. Cervantes, with technical advice from R. Bos, PEEM.

Klaus Lampe
Director General

Recommendations

Research recommendations

1. *Assess ricefield water-manipulation strategies to meet the twin goals of vector control and high rice yields; assess socioeconomic implications of adopting the most promising methods.*

   The assessment should take a collaborative, interdisciplinary approach involving agronomists, vector ecologists, epidemiologists, agricultural engineers, and agricultural economists. Studies should encompass intermittent irrigation and other irrigation practices, water control infrastructures, and field leveling.

2. *Assign a WHO assistant professional officer in the field of medical entomology to work with IRRI agricultural scientists to assess the relation between crop production practices and vector bionomics.*

   The APO's work program would be based on the short-term research priorities identified by this Workshop. This collaborative effort, consistent with recommendation 1, should include establishing a computerized database on vector-borne diseases in relation to rice production systems. This will give researchers more rapid access to such literature than is now possible.

3. *Establish the relations between agricultural management strategies and public health problems.*

   Strategies that provide dual benefits as well as those that result in conflict need to be defined.

4. *Determine the relation between chemical treatments of ricefields and changes in the flora and fauna and the subsequent effect on pest and vector species.*

   This work should be done collaboratively by agricultural and public health scientists.

5. *Determine the reasons that environmental management measures effective against vector-borne diseases have not been applied to water resource management.*

Research should address water impoundments, irrigation networks, and other catchment areas and involve engineers, sociologists, economists, epidemiologists, and vector ecologists.

6. *Collaborate with national agencies on studies of the advisability of introducing natural agents into agroecosystems.*

   Fish and botanicals such as Azolla and Neem have the potential for controlling vectors and increasing farm productivity.

7. *Research rice varieties that can be managed to minimize vector breeding.*

8. *Continue research on vector-borne disease intervention strategies for settlements and landscapes.*

   a. Study the influence of elevation of settlements and their distance from ricelands on protecting residents and temporary workers from malaria, Japanese encephalitis, and schistosomiasis. Factors to consider include water supply, sanitation, domestic animals, wind direction and other climatic conditions, behavior of vector species, and vegetative barriers to mosquito movement. Strategies to consider include placing domestic animals (with the exception of some reservoir animals such as pigs) between the ricefields and the settlement to divert vectors, treating bait animals with external or systemic insecticides, or placing mechanical traps in the vicinity of bait animals.

   b. Establish structural specifications for housing to protect occupants from vectors. Among these are window and door screens, curtains, insect-tight roofs and walls, and insecticide-treated or untreated mosquito nets.

   c. Determine the factors that have promoted or hindered the acceptance of known remedial practices to reduce disease transmission.

   d. Assess the role of health education in promoting settlement-related intervention.

9. *Evaluate the efficacy of personal protection strategies in reducing disease transmission in the community and on the farm.*

10. *Conduct sociological studies to find more effective means of motivating the community to integrate vector-borne disease control into the primary health care system of riceland agroecosystems.*

11. *Continue to embrace recommendation 4 of the Fourth report of the WHO expert committee on vector biology and control. 1980. Environmental management for vector control.*

    “Governments, if necessary with the collaboration of international organizations, should review the legislation available for regulating the development and use of natural resources in light of public health and environmental implications, introducing any complementary legal support that might be required.”

12. *Mobilize agricultural and health sciences researchers in the national programs of several disease-endemic countries to collaborate in the investigation of integrated vector-borne disease control in riceland agroecosystems.*

    Such a research network would expand realization of the importance of interdisciplinary research and enable projects on several vector-borne diseases to be conducted in a number of countries.

13. *Make policy makers and administrators aware of the principles and objectives of these research recommendations.*

Conclusions: working group on research needs

Basic research needs

Relative importance to disease of specific components of riceland ecosystems
Riceland ecosystems comprise several physical components, the ricefield proper, seepage areas, and irrigation networks, often in close association with wild and domestic animals and human habitation. The working group recognized the fundamental importance of the spatial and temporal quantification of vectors, intermediate hosts, vertebrate reservoirs of infection, and the human population at risk in relation to the design and implementation of cost-effective control strategies. The relative importance of each should also be considered in relation to different agronomic practices.

Successional changes in the biota
Extensive lists of vectors breeding in ricefields already exist. For some regions and some vectors, definitive studies of life table analysis, survivorship, time of maximum larval density, developmental time in relation to water temperature, and spatial distribution have already been published. For example, it is known that different mosquito species reach maximum larval densities at different stages of rice growth. The relative importance of such phenomena in relation to disease transmission and control needs to be established. Establishment of an inventory, over crop duration, of medically and agriculturally important insects is a high-priority, short-term goal, which may define overlaps and indicate mutual control benefits. Such an inventory, which should include potential biological control agents, will lead to the definition of areas for future research.

Assessment of vector breeding sites
Vector breeding sites can be assessed by established sampling methods although local techniques vary widely. Vector population densities vary markedly, but extensive rather than intensive sampling approaches yield more valuable data. Sampling methods should be directed at numbers/unit area to establish absolute population estimates.

Intervention research needs

Vector populations in ricefields

Water regime manipulations. The effectiveness of alternative methods of manipulating on-field water regimes to eliminate or minimize breeding sites and reduce vector populations needs to be determined, and their impact on rice yields assessed for various soil types in different rice-production systems. They are essential for devising water management methods that effectively control vector-borne diseases without reducing rice yield. Such evaluations should deal with intermittent irrigation as well as other irrigation practices.

Rice varieties that will permit the use of intermittent irrigation or periodic drainage should be developed. The role of water control infrastructure and management, including ricefield leveling, needs to be determined for the irrigation system as a whole and for the farm level. The socioeconomic implications of adopting the most promising methods also require assessment.

Alternative cropping. The efficacy of alternative upland nonrice crops, instead of double-cropped rice, to reduce vector breeding in endemic, rice monocrop areas needs to be determined. The economic impact of such crop rotations on individual farmers and the community should be studied. Research design should consider past experiences as in the Tjihea Plain, Java, Indonesia, during the 1920s.

Chemical and biological additives. Insecticides, herbicides, fungicides, and fertilizers will remain important in rice production. However, their impact on the rice ecosystem must be monitored to ensure that the main selection criterion is environmental safety rather than cost. Research on new and existing chemical control agents to determine efficacy, impact on nontarget organisms, and compatibility with the environment is necessary. Improved pesticide dispersal is needed to assure appropriate application levels without overdosing. Also, the timing of agrochemical applications must be studied to optimize both vector and agricultural pest control and minimize their harm to beneficial organisms.

Chemicals for controlling agricultural pests and vectors should be selected, and their application (including domestic residual vector-control application) timed, to minimize the potential of vectors to develop insecticide resistance.

Predators tend to move from canals and impoundments into ricefields. Therefore the value of propagating and maintaining larvivorous fish in ricefields should be investigated. The interaction of different fish species with each other, e.g., impact of *Gambusia* on the eggs of other fish, and with other beneficial organisms should be studied. Furthermore, the direct effect of fish on rice yield and on income per unit area should be assessed as well as methods to increase fish yield.

Pathogens, parasites, and predators that offer the potential for vector control should be carefully considered in the development of integrated control strategies. In general, the group endorsed the policy of using local products where possible.

IRRI research on the role of Neem in pest control and fertilizing suggests that its effect on repelling ovipositing gravid adults and on larval mortality should be studied.

The usefulness of Neem cake to prolong fertilizer life should be explored in relation to larval control. The bonuses Neem provides are an incentive to its social acceptance.

Vector populations outside the ricefield

Important off-field habitats that present problems in regard to malaria, schistosomiasis, and Japanese encephalitis include:

1. impoundments in which stagnant water is held intentionally either in fish ponds, reservoirs, or night storage or unintentionally in borrow pits and depressed areas,
2. irrigation networks consisting of primary and secondary canals, hydraulic structures, and water control devices,
3. seepage water accumulations on lands below primary and secondary canals,
4. waste water accumulation in low lying areas as a result of disposal or seepage from the ricefields, and
5. drainage water retained in low points of canals or natural channels.

Remedial or intervention measures applicable to vector-borne disease control in these off-field habitats may be classified into one of three categories:

1. proven measures that could be applied without further research,
2. measures that work only under specific conditions and may be applied cautiously or on a pilot scale, and
3. measures that need further in-depth study in a specific situation before pilot-scale application can be considered.

In category 3, selected studies should determine the measure's effectiveness in reducing disease transmission, its technical feasibility, its economy, its environmental impact, and its social acceptance. For example, there is a need for benefit-cost analysis of lining major irrigation channels with concrete, and studies on increasing flow rates in canals to minimize mosquito and snail populations.

Reducing human-vector-pathogen contact

Settlement-related measures. The epidemiologies of malaria, schistosomiasis, and Japanese encephalitis differ greatly between communities even within the same rice-growing area. However, there are many vector-borne disease control measures that can reduce human infections regardless of these differences. They include siting houses away from breeding places; draining or eliminating breeding places adjacent to human housing; tight construction of walls, roofs, etc.; window screens and bed nets; siting animal shelters away from houses, vector-breeding sites, and disease reservoirs such as pigs; and providing adequate domestic water and sanitation. Failure to implement these measures may be due to the lack of adequate information, high cost, or institutional constraints. The reasons that many settlement-related vector-borne disease control measures are not being applied should be studied and appropriate steps taken to implement them.

Community action measures. There are many methods to control vector-borne disease in communities in riceland agroecosystems. These methods include animal-baited mechanical trapping, and zooprophylaxis for adult mosquitoes, reducing or eliminating vector breeding and pathogen contact sites; improved housing; pesticides;

and community health education programs. In the case of zooprophylaxis, several examples of the use of animals to divert mosquitoes from humans are known. Recent analysis of the powerful nature of zooprophylaxis suggests that it should be investigated further. Zooprophylaxis could further reduce disease transmission if the diversionary animals were treated with insecticides. Citrus, lemon grass, Neem, or other botanicals with suspected repellent qualities could be incorporated into buffer zones around houses or villages. These crops would improve health and life style. Certain methods are unproven, but others require merely the organized efforts of the community for them to be effective. Efficacy research is needed on unproven tactics; socioeconomic studies and educational programs are necessary to the effective application of proven methods.

Personal protection measures. Personal protection strategies that combine the use of pyrethroid-impregnated clothing and bed nets with topically applied repellents provide low-cost, virtually complete protection from mosquito bites. Although the acceptance and logistics of repellents may not be adequate, the protection impregnated clothing, bed nets, and household curtains afford field workers and riceland community residents against mosquitoes should be studied. Similarly, personal protection against schistosomes, such as avoiding exposure to contaminated water and wearing boots whenever possible, should be promoted and other approaches should be identified and evaluated. Studies should include assessment of the potential for acceptance of these individual protection methods. Also, toxic and allergic reaction to pesticide exposure of the community over time should be monitored.

Other research considerations

Innovative survey methods

Surveillance systems may be available but not necessarily readily applicable. The first priority should be assigned to vector surveillance and the second to disease surveillance. Recently developed immunological techniques are powerful surveillance tools. For example, enzyme linked immunosorbent assay (ELISA) is used for sporozoite identification of malaria and for epidemiological surveys of Japanese encephalitis and schistosomiasis. Existing techniques, however, should not be neglected. Short-term investigation of agricultural surveillance methods may uncover useful overlaps. For example, identification of potential vector breeding sites by remote sensing could be applied to both agricultural pest and vector-borne disease control in the future.

System analysis and modelling

Agencies planning vector-control strategies in rice should consider a systems approach. Decision-making is holistic but follows step-by-step procedure with the output of one step becoming input for the next. A strong monitoring, documentation, and evaluation program is essential to the systems approach, permitting experience to be relevant to similar projects. The systems approach has an inherent ability and flexibility, which can account for site-specific factors. Successful application of the approach and the corresponding integrated vector-control strategies, however, requires research-generated information such as the physical components of vector habitat, vector-borne disease epidemiology, and response to specific control strategies. Models for disease prediction are the logical outcome of improved surveillance. Field data need to be integrated into existing mathematical models. Several models have been developed for arboviruses such as Murray Valley encephalitis, St. Louis encephalitis, and dengue. Simulation is an economical tool for examining the impact of multiple variables on disease transmission and further development is required.

Training recommendations

1. *Encourage information exchange between health professionals concerned with vector-borne diseases and professionals in rice research and rice-production training.*

   Rice workers should understand the relation between rice cultivation and irrigation and the vector-borne diseases that often follow. Health professionals need a better understanding of the engineering and water-management practices associated with rice farming and the constraints to altering these practices, particularly if they reduce rice yields.

2. *Include instruction in agriculture and water management, particularly as they relate to riceland ecosystems, in postgraduate courses in tropical health, medical entomology, and vector control. Include instruction on vector-borne diseases in postgraduate courses in agriculture and engineering.*

   In this way, public health professionals will become familiar with the problems and needs of rice farming. And agriculture and engineering students will learn 1) the epidemiology of vector-borne diseases, 2) the biology of riceland-breeding vectors, and 3) potential vector-control methods, particularly as they relate to changes in irrigation patterns. Guidelines for incorporating a health component into engineering curricula are available at WHO.

3. *Conduct information seminars for health and agricultural specialists to ensure they are informed of new developments in vector control and problems that may arise in the field.*

   IRRI and PEEM could organize these seminars with adequate support. PEEM should encourage ministries of health to undertake seminars through their primary health-care networks.

4. *Inventory riceland-related vector-borne diseases by country and region.*

   WHO should initiate the inventory, which should incorporate an estimate of training facilities required by country in relation to the magnitude of vector-borne disease problems, the training facilities available, and training personnel at national and regional levels. The inventory should consider training needs for public health and agricultural workers and include a list of agencies that might provide funding, trainers, supplies, and instructional materials.

5. *Inform development and national planning agencies of riceland vector-control measures as they are elaborated so they can be incorporated into project designs at an early stage.*

   Riceland vector-control measures certainly will include environmental and water management that should be included in project designs for the development of ricelands. WHO, FAO, and UNEP should share this responsibility, with PEEM serving as one information source.

6. *Prepare and distribute to extension trainers instructional materials on chemical and biological vector-control measures and on water and environmental management as soon as they are shown to be effective and economical in riceland ecosystems.*

   PEEM and IRRI could disseminate training documents on chemical and biological vector controls measures through their country contacts and collaborating agencies. Training material on water management and environmental control, however, should be distributed by IRRI. National water management and rice extension workers should have adequate training in the importance of vector-borne diseases associated with ricefields to assist them in training farmers and irrigation technicians.

7. *Train public health and agricultural workers on snail-borne diseases other than schistosomiasis.*

   Snail-borne diseases other than schistosomiasis represent an increasingly important problem in several countries where schistosomiasis is either absent or is not a public health issue.

8. *Establish a computerized database on vector-borne diseases in relation to rice-production systems.*

   This proposal, formulated under recommendation 2 of Research Needs Recommendations, applies equally to training needs.

9. *Review literature on the effects of agricultural andpublic health pesticides used in ricefields on nontarget predators of aquatic states of mosquitoes.*

   UNEP, International Register of Potentially Toxic Chemicals, IUCN, and national agencies such as the U.S. Environmental Protection Agency may have this material on hand and should be asked to assist.

10. *Enlist greater involvement by national and international nongovernmental organizations in vector-borne disease training and education.*

More effort is needed to circulate information on vector-borne diseases and their control to NGOs. PEEM organizations might initiate this information and action program through their associated NGOs. The ultimate target of training programs is the farmer and the community in which he lives. All relevant techniques, including mass media, should be used to direct training to the farmer.

Conclusions: working group on training needs

Subject matter

Any training course at whatever level should have as its first objective developing an awareness of the relation between rice production, the ecology of disease vectors, and the transmission of vector-borne diseases. Students should also be given, at a level concomittant with their training, the most important aspects of the epidemiology of those diseases with which they are most likely to come into professional contact. Finally, they should gain an understanding of the life cycles of the most important vectors of disease and, more specifically, how rice cultivation favors a particular vector. These subjects should be organized in modules, each one addressing a particular disease, rather than presenting the epidemiology of all diseases followed by details on their life cycles, ecology, and control.

The nature and scope of the subject matter in various training programs must, of course, depend on the background of the students, the length and content of the course, and whether it is part of the general curriculum for engineers or agronomists or is a special familiarization course. Whenever regular training courses are launched in a country, local training needs will have to be carefully assessed. Training may include short-term and long-term study as well as intensive workshops and specialized seminars.

If the training is given in a disease endemic country, training should include local case studies and, where possible, field visits to large- and small-scale water resource development projects. In any event the three most important diseases associated with rice production, malaria, Japanese encephalitis, and schistosomiasis should receive priority. If one or more do not exist in a given country, then the importance of mosquitoes as pests of man might be emphasized. In Asia, rice production and fish culture provide an ecological basis for transmission of other important snail-borne trematode infections such as clonorchiasis and opisthorchiasis.

The course should train the student not only in the general epidemiology of diseases and the ecology of their vectors, but in possible control methods. Emphasis should be given to environmental management measures that can be included at the planning, design, and construction phases of irrigation systems, as well as to the operation and maintenance. Control methods should consider water management, crop selection and rotation, the introduction of livestock, and other agricultural practices.

Particular attention should be given to practices to prevent or reduce vector breeding without reducing rice yield. The effects of natural or chemical fertilizers, and agricultural pesticides, including herbicides and fungicides, on disease vector populations or nontarget organisms should be included. Local manufacture of indigenous botanical pesticides should be encouraged as substitutes for imported pesticides.

Organizers of training centers do not need to be concerned about the lack of trained personnel. Specialized health training centers such as those in ministries of health or schools of medicine or public health can assist. The extent of their participation must be determined with the school of engineering or agronomy that is introducing the subject. Such schools should be encouraged to make environmental management for vector control a part of the regular curriculum and not a one-time presentation.

Students and professors should evaluate such courses to ensure that they meet the needs and interests of both.

There is a general lack of trained professional entomologists and parasitologists. More training is needed in medical entomology and vector control, particularly in the field of aquatic biology, which is especially important in the study of vectors and nontarget organisms in ricefields. The working group called frequent attention to the lack of career opportunities in these areas and the need for correcting this situation.

In large rice production regions, entomologists, parasitologists, and agronomists should be equally familiar with diseases whose vectors breed in rice ecosystems and those associated with rice-growing communities.

Entomologists/parasitologists should receive sufficient information on basic engineering and agronomic principles relevant to environmental management for vector control. Such training would ensure communication between engineers, agronomists, and entomologists/parasitologists whenever they are jointly involved in rural development in rice-production areas.

Approaches

To rapidly provide accessible training facilities for the many countries faced with vector-borne disease problems in riceland ecosystems, the basic need is for modular training courses appropriate to regional and national needs.

Successful introduction of courses depends on the collaboration of institutions with established regional and national responsibilities. A coordination center to set standards for staff and training material, ensure efficiency, and monitor training effectiveness is required.

We do not recommend new agencies to provide training staff; existing facilities should be used to the extent possible. The coordinating center could draw on these facilities and have its own advisory panel and secretariat.

The regional approach would ensure that national institutions receive training materials and course modules best suited to their needs. It would also provide a better base for identifying extension training requirements and for translating and publishing middle- and lower-level training material along the lines followed by IRRI. Production, however, may best be centralized for economy.

A possible model might be a joint initiative by IRRI, the University of the Philippines at Los Baños, the Philippine Ministry of Health, and a public health organization in Southeast Asia or the Western Pacific. An advisory panel, working on experience gained by the group, could assist in replicating the approach to meet demands in other regions, assuming that funding could be assured.

Target groups

Specific target groups should be identified early in the planning stage of extension training. The first priority and the immediate area of concern of this Workshop is the training of existing professionals who themselves will train and advise others. Agronomists, engineers, and irrigation specialists, particularly those responsible for rice production training, should understand:

- the main vector- and rodent-borne diseases associated with rice production, particularly with irrigated rice, and
- the biology and ecology of ricefield-breeding mosquitoes as main vectors in this habitat.

Equally, medical entomologists and vector-control specialists should be familiar with the principles and practices of rice culture to ensure they understand the objectives and problems of rice production.

Agricultural extension workers, especially those working with irrigation and rice growing, are a prime target group for training. And the farmer must be trained to use whatever methods are finally developed so that he can grow rice free of major vectors without sacrificing yield and quality. Persons living in disease-endemic areas, should learn to use economical personal protection and make use of appropriate health facilities.

There are special groups who must be familiarized with the problems of vector-borne disease and rice production even if only in brief, intensive training sessions. Among these are policy makers, administrators, community leaders, teachers and, where appropriate, religious and social leaders.

Institutions

Existing institutions should direct training activities, whether for agronomists and rice specialists or for entomologists. As a first step, such institutions, particularly those able to train the trainers, should be identified and established as collaborating agencies. The UN system and associated agencies offer a ready starting point because they embrace all of these subject areas in relation to the development of riceland ecologies.

Potential funding sources for training activities include the World Bank and Regional Development Banks (ADB, AfDB, WADB, IADB), the UN Development Programme, bilateral agencies, and a number of foundations. The operational and support agencies should include FAO, WHO, and UNEP, together with their PEEM collaborating centers, and various CGIAR organizations—especially IRRI and WARDA with possible participation from CIAT and IITA. IIMI and regional schools of tropical agriculture could participate. Some funding agencies may extend their role to the implementation and operation of training activities, among them the World Bank, which is already engaged in such work.

Training agencies need not necessarily develop their own staffs. They likely will recruit personnel from existing institutions. Training personnel may be borrowed from schools of tropical medicine, schools of public health, and universities throughout the world. National institutions in rice-growing countries would be particularly rich sources of personnel familiar with riceland ecology.

Professional engineering and agronomical organizations, with probable support from ICID, are particularly well suited for training collaboration.

Welcome address

M. S. SWAMINATHAN

Welcome. We are very happy that a somewhat different group than we normally have at our meetings and conferences is here today. You know, in genetics we work on hybrid vigor—heterosis—and many times, the more distantly related the genotypes, the greater is the heterosis. So a group of health professionals interacting with agricultural rice scientists should lead to an even more beneficial and heterotic vigor in terms of the products of discussion. We are particularly grateful to PEEM, the primary sponsor of this workshop. We are happy that IRRI is now one of six PEEM collaborating centers, and we are grateful to WHO for agreeing to have this particular meeting at IRRI. I also want to thank the USDA/RMMP, the other major cosponsor. We are also grateful to USAID for its grant to WHO to support workshop participants.

In the week to come, IRRI scientists will report on what is happening in the global rice scenario, the role of irrigation, or water conservation (as is the case in rainfed areas), and rice production. Suffice it to say that the area under irrigation has been expanding, and irrigation has certainly made a strong contribution to overall rice production the last 20 years. Without water it becomes difficult to grow high-yielding varieties, to give nutrients, and so on. So water holds the key to both stability and higher production.

IRRI worked initially entirely on irrigation water management, but 3 years ago our trustees decided to slightly change and enlarge our work, partly because the International Irrigation Management Institute had come to Sri Lanka. We enlarged our own Irrigation Water Management Department, renaming it the Water Management Department, and focusing on both irrigation water management and rainfed water management for water conservation, drainage, and soil problems such as salinity and alkalinity.

Above all, our concern is with the associated environmental problems connected with water, whether soil problems or those we are going to discuss in this particular workshop on vector-borne diseases. That is the fourth stream in our water management department. Obviously we have no expertise, and the first rule here is to take on only such research and training activities in which we have a comparative advantage.

In the area of human vector-borne diseases, we have no advantage at all, but in all such areas we would like to be a collaborator and try to help other institutions. We hope this interaction with agronomists, agricultural scientists, irrigation engineers, water technologists, entomologists, etc. will be helpful, and we look forward to a WHO scientist being located here.

We now put greater emphasis on sustainability of the production process—the ecological sustainability—and this is where the human environment becomes exceedingly important. And it is where the associated problems of health care—plant health, animal health, and human health—also become exceedingly important.

We are going to have a program at IRRI on the impact of new technologies on the environment and this particular workshop fits in ideally with this new stress on environmental issues in relation to rice production. We are happy that we will have a blend of both agricultural rice scientists and health workers at this meeting and we hope that this particular interaction will be very helpful.

I want to state that here at IRRI, we measure every workshop by both input and output. The input is all the planning that has gone into it as well as your papers. The output will certainly be a publication, which will be useful in terms of a compilation of the state of the art but we hope that along with the publication we will lay the foundation for a more active research cooperative.

We make a distinction here between a research network, which is more structured in terms of research coordination and monitoring, and a research cooperative in which scientists belonging to totally different institutions and disciplines come together to work under a continuing partnership. I hope that at the end of this meeting we will have laid a more solid and enduring foundation for a research cooperative between the people who are working on vector-borne diseases in this part of the world—whether malaria or Japanese encephalitis or schistosomiasis—and our rice workers, not only those at IRRI but our partners in the national research systems. We have excellent linkages between institutions that work with us and through them we become more acutely aware of these issues and work jointly wherever our scientific interests will be better served by a partnership. We should continue to do that.

We hope some of you will help us initiate our program on the impact of new rice technologies on the environment when it gets better organized. We are hoping to get some guidelines on what IRRI may be able to contribute from this particular workshop. So, ladies and gentlemen, I extend to you a very warm welcome and thank you for coming.

Remarks on behalf of PEEM

R. Sloof

It is a great pleasure for me to welcome you, on behalf of the Panel of Experts on Environmental Management for Vector Control and its three supporting organizations WHO, FAO, and UNEP, to this workshop.

When, during the first two decades following World War II, the concept of development cooperation between industrialized countries and the developing countries gradually took shape, projects were organized in a predominantly sectoral manner. This sectoral approach was also reflected in the United Nations system itself. Although some level of coordination existed from the start, it was basically FAO that dealt with agricultural development and food production, WHO and UNICEF with human health, UNESCO with education, UNEP—which was established later in the 1970s—with the human environment, etc.

Within these structures, many of the most urgent problems belonging strictly to the realm of one particular sector could indeed be adequately dealt with. However, many issues of a more multidisciplinary character could not be tackled effectively. The history of vector-borne disease control may serve as an example of this vertical approach.

With the development of cheap and effective insecticides such as DDT in the 1940s, eradication of malaria, for instance, was considered a realistic goal for many parts of the world. And indeed, in some parts of the world malaria was eradicated and has not been reintroduced to the present day. However, as is well known, in many other parts the original goal had to be scaled down to malaria control rather than eradication, mainly due to a failure to address numerous operational problems and the rapid development of insecticide resistance.

Since the 1970s, WHO has advocated integrated control, integrated vector control in particular, with a chemical, a biological, and an environmental management component whenever feasible. By that time there was a growing realization that intersectoral collaboration was crucial to a successful solution of many problems, whether in health, agriculture, or any other field, and for sustaining the achievements. Although tremendous technical progress had been made in these fields (the outstanding achievements of IRRI in the development and introduction of highly effective rice production technologies, and the development of new vaccines and their implementation through the WHO/ UNICEF Expanded

Programme for Immunization), relatively little was known of how these new developments affected other sectors. And little was known of how, in the end, the entire conglomerate of developments would affect the quality of life of the people in the less developed countries. In fact, there was a growing awareness that in several cases, developments in one sector had adversely affected another. The realization of this has led the way to a more holistic, a more truly integrated approach toward problems in agriculture, in health, and in other fields related to development.

Integrated rural development has become a key expression and includes all the relevant elements. Among many other things, this led to the establishment of PEEM in 1981, to address vector-borne disease problems associated with water resource development. With the holding of this *Workshop on Research and Training Needs in the Field of Integrated Vector-borne Disease Control in Riceland Agroecosystems of Developing Countries,* we have, in my opinion, reached a new milestone in the collaboration between experts in health and experts in agriculture.

I am also pleased that we will be able to benefit from the extensive experience of the USDA Riceland Mosquito Management Program, a group that has had a pioneer role in this field. WHO, FAO, and UNEP have great expectations of the outcome of this workshop and of follow-up collaboration with IRRI based on the research and training needs identified during this week. I wish you all a very good workshop and very fruitful cooperation.

Introduction

Vector-borne diseases may be parasitic, bacterial, or viral. They are distinguished by their mode of transmission.

In the majority of vector-borne diseases, the infective agent is carried from one individual to another by an arthropod species of the insect class. They include malaria, the filariases, the trypanosomiases, the leishmaniases, and a number of virus infections (arthropod-borne or arboviruses), such as Japanese encephalitis and other encephalitides, yellow fever, and dengue.

In many cases the pathogenic organism goes through some of its developmental stages inside the vector, but in all cases it multiplies, sexually or asexually, inside the vector. Schistosomiasis (bilharzia) follows a similar pattern. The difference is that the aquatic or amphibious snail species in the transmission cycle act as intermediate hosts for the asexual stages of the schistosome parasites. They do not carry the disease from one human to another. The infective stages of this parasite, the cercariae, swim about freely in contaminated water after they have been shed by the snails.

Malaria, schistosomiasis, and Japanese encephalitis are important vector-borne diseases associated with rice production in developing countries. Their causal agents are directly or indirectly associated with aquatic environments through the ecological requirements of certain stages in the life cycles of the pathogens or their vectors. **(Vectors is used in a broad sense and includes primary and intermediate vertebrate and invertebrate hosts and animal reservoirs of human and animal diseases.)**

Similarly, rice production is dependent on water. Many common rice varieties need continuous flooding for their development and optimum yield. In many instances the rice agroecosystem perfectly fits the ecological requirements of pathogens or their vectors.

The collaborative research of agronomists, vector ecologists, vector-control specialists, epidemiologists, civil and agricultural engineers, and, sometimes of sociologists and economists, will be required to solve the inherent problems and clarify the relevant issues.

Although substantial knowledge exists in each of the relevant specialties, workshop participants noted that agricultural and medical specialization had created a communication gap with the result that measures were promoted or adopted for one purpose without due consideration of the other. The development of insecticide resistance by vectors exposed to agricultural pesticides was noted because it may negate epidemic control efforts. For example, cotton spraying along the American Pacific Coast has led to multiple resistance in the local malaria vector species *Anopheles albimanus.*

There is a need first for historical literature reviews to provide a basis for developing more effective vector-borne disease control strategies. Continued pressure for more rice production implies more intensive cropping in established rice-growing regions such as South and Southeast Asia and expansion into Africa and Central America. Some research would be directed toward the control of existing health problems and some toward prevention.

Appropriate training programs are the key to the successful application of effective and acceptable solutions to the control of vector-borne disease transmission associated with rice production in the tropics and subtropics.

The training requirements are unique: disease problems must be identified and investigated by health professionals including biologists, epidemiologists, entomologists, and parasitologists. Solutions will require extensive research on the epidemiology and ecology of the diseases and on the agricultural practices related to them. That will require collaboration between health scientists, agronomists, and engineers.

It is unlikely that most health groups will have ready access to all agricultural workers. Thus, the main objective must be to train the trainers, those persons who will train agronomists, irrigation engineers, agricultural extension specialists, and others who deal with the agricultural community at the grass-roots level. These agricultural trainers will be far more aware than most health personnel of how changes in water management practices can be explained to farmers and irrigation technicians. They will also be more aware of the constraints and the reasons for changes in rice cultivation to suppress vector production and the subsequent transmission of disease.

Ultimately, farmers and extension workers must apply the solutions in the field.

The impact of rice production on vector-borne disease problems in developing countries

N. G. GRATZ

Expanding human populations in the tropical developing countries require a continuing expansion of food production. For most of Southeast Asia and the Western Pacific and for increasing areas of Africa and Latin America, this implies great increases in irrigation for rice production. In many countries this at times has resulted in substantial increases in vector populations, particularly mosquitoes and to some degree snails. In most of the tropical disease-endemic countries that has meant an increase in vector-borne disease incidence and prevalence. This has been particularly marked in relation to Japanese encephalitis, which is transmitted almost entirely by ricefield-breeding mosquitoes, and with malaria. In some geographical areas there has also been an increase in schistosomiasis prevalence, particularly from transmission in rice irrigation and drainage canals. Although these increases in disease transmission have not been uniform, it should be remembered that in some areas intended for increased rice production, especially in Africa and Latin America, malaria and a number of arboviruses, which can be readily transmitted by mosquito species breeding in ricefields, are already endemic. Anopheles *gambiae,* the main vector of malaria in Africa, is often found in increased densities in ricefields. Ricefield development for the most part will take place in areas with an already heavy burden of vector-borne diseases. Health and agronomic professions must work closely to avert additional transmission of vector-borne diseases by preventing further vector production in ricefields through economical water or environmental management that will not reduce rice yields.

In 1985, rice was grown on about 145 million ha worldwide. The irrigated rice area totaled 77 million ha, or about 35% of the 220 million ha irrigated for all crops. Although rice provides the staple food for nearly 60% of humankind, in many parts of the world its cultivation frequently carries penalties in the form of several diseases closely associated with rice production, many of which are vector-borne. This paper reviews some of these vector-borne diseases and the extent to which they occur in the endemic countries.

Japanese encephalitis

Few, if any, of the vector-borne diseases are more closely associated with ricefield-breeding mosquitoes than the arbovirus Japanese encephalitis. The disease is a serious public health problem in many countries ranging from the southeastern parts of the USSR through Korea to Indonesia in the south, and west to India and Sri Lanka. Although it appears to be subsiding in China, Japan, and the Republic of Korea, it has been spreading in parts of Bangladesh, Burma, India, Nepal, Thailand, and Vietnam (Umenai et al 1985). Among the reasons for the increases in the incidence and distribution of the disease is the shift to irrigated rice cultivation from dryland crops, and the establishment of large, modern pig farms (pigs are one of the most important reservoirs of the disease in certain countries). Where the incidence of the disease is diminishing, it is probably due to the increased use of pesticides, both

Table 1. Japanese encephalitis in various countries.

Country	Geographical distribution and year	Cases annually (no.)	Case-fatality rate (%)	High-risk groups
Burma	Shan State since 1974; other areas since 1977; no cases since 1980	543	15-21	All age groups
China	All provinces (except Xinjiang, Shanghai, and Tibet)	> 10 000	10	Children <15 yr old
India	South India only (before 1970)	100 (average)	21-40	Children <15 yr old
	North and northeast: 1978	7463		
	1979-83	1716-3894		All age groups
Japan	Western prefectures: before 1967	> 1000	30	Shift to older age groups
	after 1967	100 (average)		
Republic of Korea	All provinces (prevalent in southwestern part before 1969)	> 1000	>40	
	During the 1970s	86 (average)	5.8	Children <15 yr old; modest shift to young adults
	1982	1179	3.3	
	1983	139	10.8	
Nepal	First outbreak in 1978 in the south: 10 of 14 administrative zones	55-843	35.4	All age groups
Thailand	North and northeast: 1970	986	20-30	Children <15 yr old
	1971-79	1600		
	1980	2143		
	1981	2432		
	South Thailand	Sporadic cases		
Sri Lanka	All provinces	Sporadic cases		Children <15 yr old
Indonesia, Malaysia, Singapore		Sporadic cases		

Source = Umenai et al (1985).

insecticides and fungicides, in agriculture as well as the effect of the widespread vaccinations of humans and pigs in some countries. Although in some countries the reasons for increases or decreases in incidence are fairly apparent, in others they are not well understood. The epidemiological situation is as shown in Table 1 (Umenai et al 1985).

Many potential mosquito vectors of Japanese encephalitis have been reported, but only a limited number are thought to play an important role during human outbreaks. Pant (1979) listed the most important as *Culex tritaeniorhynchus* and *C. vishnui* in the temperate regions and *C. tritaeniorhynchus, C. vishnui, C. gelidus,* and *C. fuscocephala* in the tropics and subtropics.

As Pant observed, all these species have one thing in common: they breed primarily in ricefields whether in temperate or in tropical zones. Generally, the population densities of these species of mosquitoes expand as land under rice cultivation expands. The bionomics of the vector species and the epidemiology of Japanese encephalitis differ markedly from one country to another.

Several of the Japanese encephalitis endemic countries are pursuing active vaccination campaigns to prevent transmission of the disease and there have been some attempts to control the mosquito vectors. Considering the extremely large areas covered by rice, this is not an easy task. Although it has sometimes been possible to significantly reduce vector densities by insecticide treatment—usually by aerial applications (Self et al 1973), larviciding, and residual sprays, particularly to pig pens—the treatments are costly and are effective for only a relatively brief period. Although insecticidal control is certainly justified during an epidemic outbreak, as occurred in Sri Lanka in 1985-86 with more than 400 cases in a relatively limited area (WHO 1986a), it is doubtful that it can be used routinely anywhere. Control of transmission must, therefore, depend either on control of the vector population in ricefields or on vaccination or on both.

There has been some success in preventing feeding by the vector through the use of insecticide-impregnated curtains or bed nets in houses. Where this has been tried, usually with a pyrethroid insecticide, it has considerably reduced mosquito feeding and survival in treated rooms. Additional protection may be gained by improving house construction and adding screening or even siting villages away from ricefields and livestock to make them less subject to mosquito attack.

Malaria

Some 92 to 98 million new cases of malaria are estimated to occur globally every year (WHO 1986b,c). That is a heavy burden on rural, agricultural populations, particularly those in the tropics who are also burdened by the morbidity from other diseases (many of them vector-borne). In the majority of the malarious countries of Asia, a reduced level of malaria is maintained by widespread antimalarial measures including residual application of insecticides, some larviciding (mainly in urban areas), and the widespread use of antimalarial drugs. Drug resistance in the parasite *Plasmodium falciparum* is already widespread and is rapidly spreading further. That, combined with the problem posed by vector resistance to insecticides, severely hampers the control of malaria transmission.

It is difficult to determine how much of the malaria transmission that occurs in Asia, Africa, and the Americas is due to mosquito vectors that breed in ricefields. What is certain is that ricefield-breeding *Anopheles* do account for a great deal of the malaria transmission in rice-growing areas of the world. Some idea of the magnitude of this transmission can be obtained from the number of important malaria vectors that breed in ricefields in various parts of the world. Among them are *Anopheles sinensis* and *A. minimus* in China and elsewhere in the Western Pacific; *A. philippinensis* in the Philippines, Indonesia, and many other areas of the Western Pacific and Southeast Asia; *A. aconitus* and *A. barbirostris* in Indonesia; *A. culicifacies* and *A. nigerrimus* in India, Sri Lanka, and many other parts of Southeast Asia; *A. sergenti* and *A. pharoensis* in the Middle East; *A. gambiae* complex and *A. funestus* throughout much of Africa; *A. albitarsis* and perhaps to some extent *A. albimanus* in Central and South America; and *A. freeborni* in North America. This list is not exhaustive and many other species of anopheline vectors breed in ricefields and runoff water from ricefields to some extent or another. Bang and Pant (1983) reviewed the disease vectors, malaria vectors among them, breeding in ricefields in Asia.

It should come as no surprise to contemporary workers that there is an association between ricefields and malaria vectors. Hill and Cambournac (1941) described malaria in Portugal in the late 1930s, reporting the disease was limited principally to the rice-growing regions in the southern part of the country. More than half the stable population of the villages near the ricefields was attacked each year and about 75% of the temporary workers became victims. They reported that the daily *Anopheles* production was as high as 20,000 adults/ ha.

Hill and Cambournac also described a 1935 field trial of intermittent irrigation of ricefields, concluding that rice quality and quantity did not suffer. In fact, there was usually some yield increase and a considerable savings in water. Under ordinary conditions, anopheline larvae were reduced more than 80%. In some cases the breeding of anophelines was entirely controlled. Numerous other examples of the relation between rice production, irrigation, mosquitoes, and malaria could be given, but perhaps few more graphic than this one.

Intermittent irrigation is still being considered and has been adopted in some countries, although not for the specific purpose of mosquito vector control. Nevertheless other workers have obtained similar results (Kamimura and Watanabe 1973). That the problem was addressed and a solution offered more than 45 yr ago brings to mind George Santayana's observation: "Those who cannot remember the past are condemned to repeat it."

Filariasis

There are three species of lymphatic filariasis, *Wuchereria bancrofti, Brugia malayi,* and *B. timori,* and it is estimated that some 90.2 million persons are infected. More than 50 million of them live in Asia; China, India, and Indonesia account for two-thirds of the total (WHO 1984). Although the prevalence of lymphatic filariasis has decreased in China due to an active and effective control campaign, it has increased in other countries. Much of the increase is due to urban filariasis transmitted primarily by *C. quinquefasciatus,* which breeds primarily in highly polluted water in urban areas, but also in some rural areas. Some resettled migrants in Indonesia are being infected by *B. malayi* in their new homes. The increase is due to vector species breeding in ricefields, a situation that is likely to occur elsewhere as well.

WHO (1984) also reports that dam building and irrigation, especially for rice cultivation, are resulting in increased vector populations such as species of the *A. gambiae* complex in Africa and *A. barbirostris* in Indonesia. Both species are important vectors of malaria; whatever measures are undertaken to achieve control of one disease will probably be effective for the other.

Schistosomiasis

Schistosomiasis is now endemic in more than 74 countries. In many of them, transmission of the disease is associated either with ricefields themselves or the irrigation systems. Most of the methods that would limit mosquito breeding in ricefields would also be effective against the snail intermediate hosts of schistosomiasis.

Conclusion

There is ample evidence to link ricefields, vectors, and the transmission of a number of important vector-borne diseases, of which only the most important have been discussed here. There is equal evidence to link the increase of agricultural areas devoted to ricefields and the increased transmission of certain vector-borne diseases.

The main problem is not a lack of proof of the relation between rice growing and vector-borne diseases, but what can be done about it. Those responsible for the control of vector-borne diseases must remember that the purpose of growing rice is to provide the most important staple food for the majority of humankind. The purpose of water in ricefields is to irrigate the rice, but this also happens to breed certain vectors in abundance. Both very early and very recent work have shown it is possible to obtain high rice yields without multiplying vector populations, and the challenge is to determine if modified cultural practices can be effectively introduced and economically taken up by farmers. Unless the method or methods proposed produce at least as much rice, and unless the already heavy workload of the farmer is not increased, it seems unlikely that they will be accepted. Because few other methods of vector control, whether chemical or biological, are economically feasible to control vector populations over the vast rice-growing areas, it is clear that a high priority must be given to studies of irrigation practices and their relation to vector production. If that is to be done well, there must be joint work between the agriculturalist, the irrigation engineer, the entomologist, and the epidemiologist.

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Author's address: N. G. Gratz, World Health Organization, Geneva, Switzerland.

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Tropical rice agroecosystems: characteristics, distribution, and future trends

D. P. GARRITY

The tropical rice-growing agroecosystems are diverse at the micro and macro levels. The major classes and subclasses of ricelands are differentiated by water depth and dependability, with wide variation recognized between rainfed agroecosystems. Hydrological factors, particularly the annual length of flooding, heavily impinge upon the ecology of vector-borne diseases. The relative distribution of ricelands in each of the major hydrological classes also varies between tropical regions as does the prospect for riceland expansion. The geographical zones of disease prevalence raise many questions in relation to the distribution of rice agroecosystems. In Africa and Latin America there is enormous potential to develop wetlands for rainfed and irrigated rice production. Development of these resources is inevitable to meet the exploding demand for rice, but it will require careful attention to disease management at the outset. In Asia, which is largely self sufficient in rice, new irrigation development is slowing, but more attention to the health aspects of sustained rice production systems can be expected. Rice and medical scientists face a major challenge to develop more comprehensive databases on the ecology of vector-environment-management interactions specific to each rice agroecosystem to ensure effective integrated vector-control methods.

Rice is the most important crop in the developing world in value of production and in contribution to diet. It is also the main source of employment and income of the rural populations in those regions. Ninety-five percent of the world's harvested rice area of 146 million ha is in the developing countries. Growth in rice production averaged 2.9% globally during 1970-85, and must continue to increase at nearly this rate to meet the projected demand at the end of the century (FAO 1981).

Millions of small-scale farmers greatly modify their ricefield environments to increase the yield of their rice crops. These modifications predominantly involve changes in the surface hydrology of the ricelands to control the water depth, stabilize water supply, and lengthen the hydrological year for rice production. Rice agroecosystems often create extensive habitats favorable to the snail intermediate hosts of schistosomiasis, and conducive to the mosquito vectors of malaria, lymphatic filariasis, and the arboviruses. There is also continuous development of new riceland in areas of endemic vector-borne diseases, a process which may accelerate in the future, particularly in Africa (Moorman and Juo 1986). This matter demands greater attention from rice scientists, for they have seldom incorporated into their research an awareness of the interaction effects of improved rice-growing technology vis-a-vis the major disease vectors.

Disease control strategies that are an integral part of the rice production process are required in each distinct rice agroecosystem. Rice scientists, medical entomologists, and public health specialists need to understand the interaction between the occurrence and prevalence of the disease vectors and the micro and macro aspects of rice agroecosystems. Detailed ecological data are required to develop integrated, practical methods of environmental management to control vector multiplication.

The tropical rice-growing agroecosystems are diverse. For many years workers have attempted to characterize and classify these agroecosystems to more effectively target rice research and extrapolate the knowledge and new technologies developed (Garrity et al 1987, Huke 1982, IRRI 1984, Moorman and van Breeman 1978, O'Toole and Chang 1979). The perspective of these studies has been on how ecological and management factors interact in determining the productivity of the rice plant. It is important that we more explicitly consider the parasitic diseases associated with rice culture as important elements of rice agroecosystems.

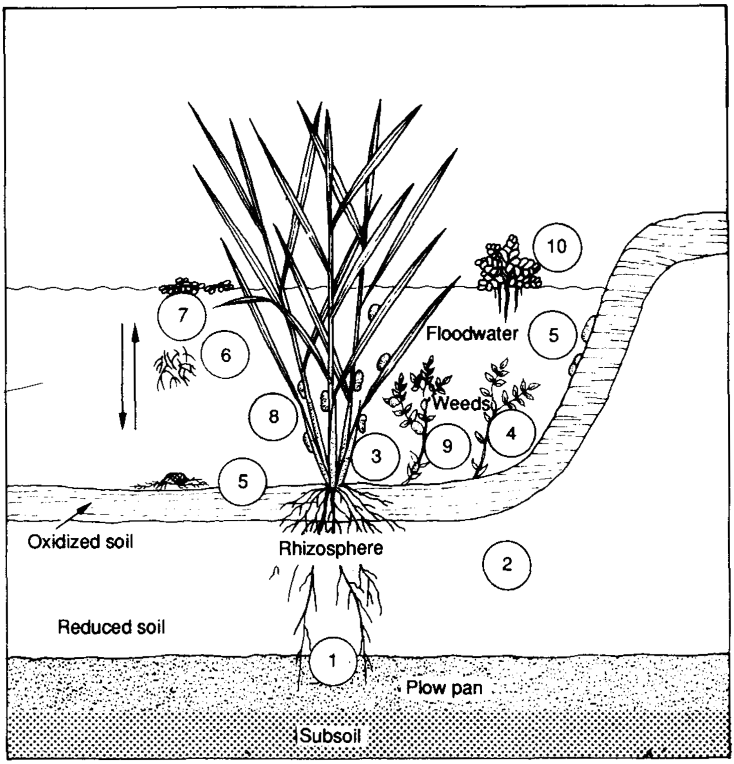
This paper will discuss the major factors that characterize and differentiate tropical rice agroecosystems. It will then outline the distribution of these agroecosystems across the three tropical continents. Relations between the distribution of the rice agroecosystems and the major vector-borne diseases, particularly the association between length of the hydrological year and the geographical distribution of the two major water-related diseases, malaria, and schistosomiasis, will be covered briefly. Finally, the paper will examine future trends in rice area expansion and irrigation development, with emphasis on the future of rice agroecosystems in Africa.

The ricefield environment

A flooded ricefield is an agroecosystem that is frequently disturbed by farming practices, i.e., tillage, irrigation, fertilization, crop establishment, and weeding, and by natural phenomena such as rainfall and flooding, which result in extreme instability on a short time scale during the crop cycle, but relative stability on a long time scale (Watanabe and Roger 1985).

Flooded ricefields are eutrophic systems with exceedingly high recycling rates of nutrients and energy, as exemplified by the rapid succession of algae. The ricefield agroecosystem (Fig. 1) is composed of five major subsystems (Watanabe and Roger 1985): 1) the floodwater; 2) a thin (about 1 cm) oxidized soil layer at the soil-water boundary; 3) a reduced puddled layer; 4) the subsoil, which is reduced when the water table is high, and oxidized when well-drained; and 5) the rice plant.

In each subsystem are lower level subsystems in which the biotic communities develop. The major components of the total biomass in the standing water are aquatic invertebrates, aquatic submerged and floating weeds, phytoplankton, zooplankton, and bacteria.

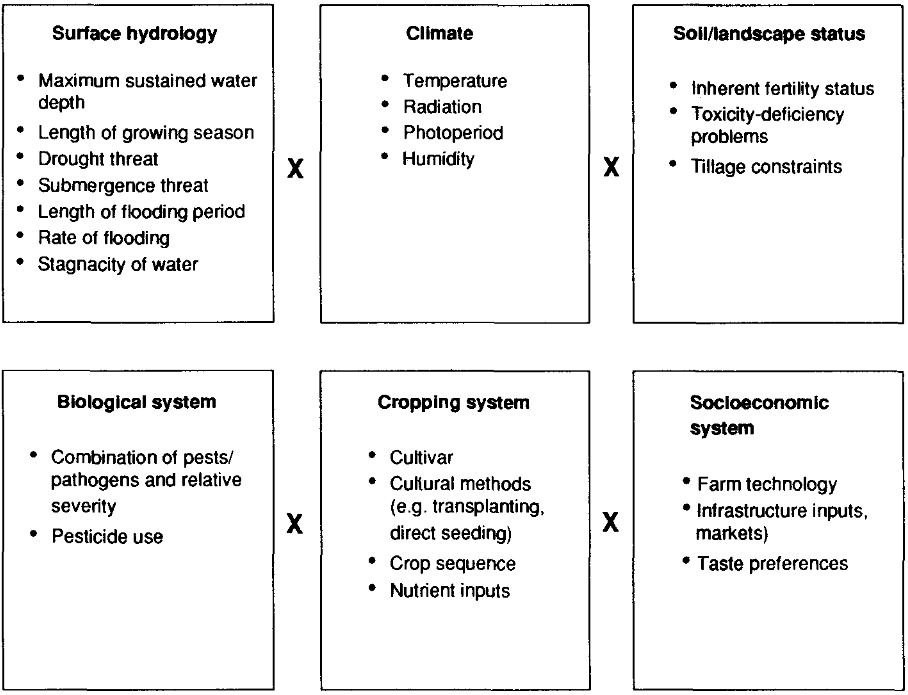


1. Diagram of environments and N2-fixing components in a ricefield agroecosystem. *N2-fixing bacteria:* 1) associated with the roots, 2) in the soil, 3) epiphytic on rice, 4) epiphytic on weeds *blue-green algae,* 5) at soil-water interface, 6) free floating, 7) at air-water interface, 8) epiphytic on rice, 9) epiphytic on weeds, 10) *Azolla* (Roger and Watanabe 1986).

The ecology of the rice environments exhibits enormous spatial variation due to extremes in the climatic, soil, and hydrological conditions under which the crop is grown. Rice is cultivated from 53 °N latitude to 40 °S, with most ricelands near sea level, but some are at elevations as high as 3,000 m. The crop is grown in both subtropical arid desert areas and humid equatorial areas. Air and water temperatures and humidity regimes vary across a wide spectrum. Solar radiation during the growing season ranges from less than 10 to greater than 25 MJ/m^2per d. The main rice-growing environments have radiation between 12 and 20 MJ/m^2per d.

Soil quality (both chemical and physical) exerts major effects on the rice agroecosystem, particularly when water control is inadequate. Rice soils vary in inherent fertility, from fine sands in northeast Thailand with a cation exchange capacity (CEC) as low as 0.9 meq/ 100 g, to high base-status, alluvial clays in the Philippines with >40.0 meq/ 100 g CEC. Adverse soils are numerous and widespread. Among the more common adverse conditions are P deficiency, salinity, acid sulfates, and organic soils of low bearing capacity (IRRI 1987).

Rice agroecosystems at the macrolevel are conceptualized as a complex of interactions between physical, biological, technological, and human factors (Fig. 2).



2. Major factors that interact to determine a rice agroecosystem.

The factors emphasized in the figure correspond to those that are crucial to the grain yield of the agroecosystem. When the goal of management is extended to minimizing or eliminating parasitic disease vectors in addition to increasing yield, the perspective from which the rice agroecosystem is viewed changes considerably. Much more interdisciplinary attention is needed to thoroughly understand (conceptually and quantitatively) the mosquito and snail vector populations as they relate to the dynamic physical, biological, and management factors, which characterize the range of important classes of ricefield agroecosystems.

Hydrological variation in rice agroecosystems

The predominant role of water depth and dependability of the flooding regime in delineating rice environments is well recognized. Current terminology (Khush 1984) considers five dominant environments based on the maximum sustained depth of water in the ricefield (Table 1):

- irrigated, with controlled shallow water depth (5-10 cm),
- rainfed lowland, with uncontrolled shallow water depth (1-50 cm),
- deep water, with maximum sustained depths from 50 to 100 cm,
- very deep water, more than 100 cm deep, and
- upland, with no surface flooding.

Table 1. Terminology for rice growing environments (IRRI 1984).

1. Irrigated
    a. With favorable temperature
    b. Low-temperature, tropical zone
    c. Low-temperature, temperate zone

2. Rainfed lowland (0-50 cm)
    a. Rainfed shallow, favorable (0-25 cm)
    b. Rainfed shallow, drought-prone (0-25 cm)
    c. Rainfed shallow, drought- and submergence-prone (0-25 cm)
    d. Rainfed shallow, submergence-prone (0-25 cm)
    e. Rainfed medium-deep, waterlogged (25-50 cm)

3. Deep water
    a. Deep water (50-100 cm)
    b. Very deep water (>100 cm)

4. Upland
    a. Favorable upland with long growing season (LF)
    b. Favorable upland with short growing season (SF)
    c. Unfavorable upland with long growing season (LU)
    d. Unfavorable upland with short growing season (SU)

5. Tidal wetlands
    a. Tidal wetlands with perennially fresh water
    b. Tidal wetlands with seasonally or perennially saline water
    c. Tidal wetlands with acid sulfate soils
    d. Tidal wetlands with peat soils

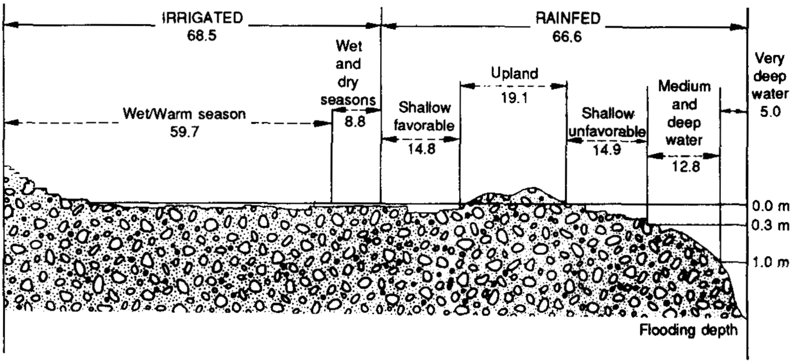
Figure 3 shows the relative area of each of these classes of riceland for the world as a whole.

Irrigated ricelands

About 77 million ha (53% of the world's rice area) are irrigated and usually have adequate water throughout the growing season. The proportion of irrigated riceland in the developing world is about one-half. Because rice grown at higher latitudes and elevations is predominantly irrigated, the main subdivision of irrigated lands was based on temperature regime (Table 1).

A crucial factor distinguishing different classes of irrigated ricelands with respect to the disease vectors is the time water is available to keep the soil submerged for rice growth, or the length of the hydrological year. About 8.8 million ha (13%) of the world irrigated rice area are double-cropped to rice (Fig. 3). The remainder is cropped once, but may be followed by other upland crops with or without irrigation. Rice double-cropping is universal in the tropics wherever year-round irrigation water is available. Double-cropping in the subtropics is limited due to seasonally cool temperatures, and rice is therefore rotated with wheat or other irrigated cool season crops.

Rice production in year-round irrigated areas is highly productive, but shallow flooding is maintained for a large portion of the year. This situation is highly



3. Relative areas of the world's riceland by water regime (million ha). Horizontal extent of each class is approximately proportional to the area. Terminology follows that of Khush (1984).

conducive to the sustained multiplication of disease vectors wherever weather and microclimatic conditions are suitable. In China, which accounts for 38% of world rice production on 23% of the harvested area, more than 90% of the riceland is irrigated. Double- or triple-cropping of rice is common in southern China, and *Schistosoma japonicum* is endemic throughout the rice-growing area.

In Nigeria, Shiowaya et al (1986) observed that the snail vectors of *S. mansoni* and *S. haematobium* were common in rice irrigation schemes where the water table was perennially close to the ground surface and water was permanently present. However, in irrigation schemes where there was a deep water table with a long fallow period in the dry season, no intermediate hosts were observed.

The adoption of modern, semidwarf rice cultivars and improved management are strongly associated with irrigated ricelands. The modern cultivars have shorter stature (80-100 cm) compared with the older cultivars, which are usually taller than 130 cm. This may have distinct implications in mosquito vector control (Mather and That 1984). Variations in plant height and canopy architecture of the rice cultivar affect the mosquito habitat. The degree of shading determines in part the suitability of ricefields for colonization by different mosquito species and potential predators. Modern varieties have an erect plant type, allowing more sunlight to penetrate the canopy even though the leaf area index is high. Whether or not canopy differences in rice cultivars have a practical effect on the colonization of mosquitoes has not been determined. However, the wide variation in preference for shade by different *Anopheles* species seriously complicates the use of cultivar canopy differences as a vector management tool.

Manipulation of the water regime in irrigated ricefields has definite potential for regulating vector populations. Luh (1984) has shown that intermittent irrigation reduced mosquito larval populations 80-90% and increased grain yields 13%. Intermittent irrigation is not practiced widely in the tropics or subtropics at present. It requires discipline and expertise in irrigation system management which exceeds that currently available in most irrigated areas. However, the incentive for decreasing water use to enable more area to be irrigated is a major additional advantage of the intermittent irrigation.

Rainfed lowland rice

Rainfed lowland rice includes the unirrigated ricelands which flood for at least a portion of the crop cycle from 1 to 50 cm in depth. The rainfed lowlands are a complex array of physical environments, which vary enormously in the amount and duration of rainfall, depth of standing water, duration of soil submergence, water deficit and flash flood frequency, soil type, and topography.

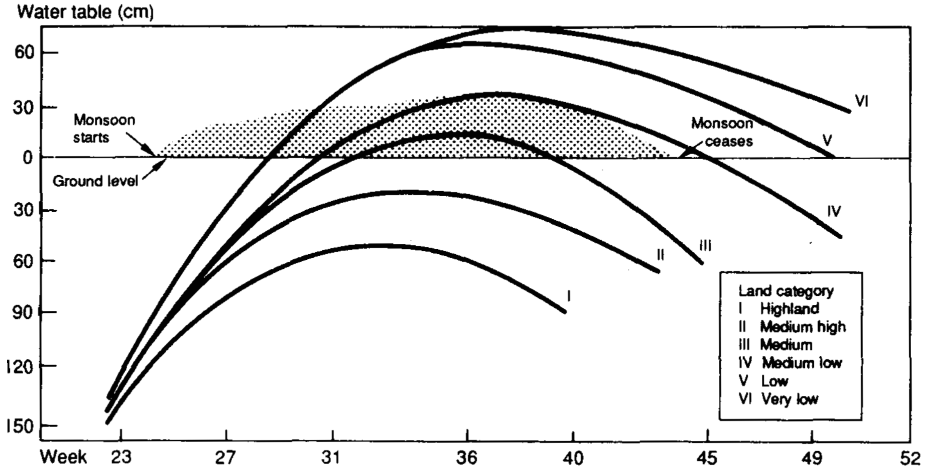
Rainfed lowland rice is subdivided into five major categories:

1. rainfed shallow, favorable;
2. rainfed shallow, drought-prone;
3. rainfed shallow, drought- and submergence-prone;
4. rainfed shallow, submergence-prone; and
5. rainfed medium deep, waterlogged.

The wide range of surface hydrology of the rainfed ricelands was illustrated by Lenka (Fig. 4) for eastern India. After the monsoon begins, landscape position dictates how high the water table will rise and the length of time the land will remain flooded.

Much rainfed rice is grown on gently to steeply sloping terraces in areas that are difficult to irrigate. Moorman and van Breeman (1978) defined these as pluvial ricelands, because the source of surface water is limited to rainfall. Ricelands at lower toposequence positions may be influenced by surface or subsurface inflow from a high groundwater table. These are termed phreatic ricelands and have a more dependable water regime.

Thus, the position of the ricefield in the landscape strongly affects soil conditions and the water availability, and therefore the cultural practices and cropping pattern potential. Farmers are highly conscious of these differences and local systems of land classification that reflect a detailed knowledge of riceland production capability are used in many areas.



4. Variation of water table in ricefield of Orissa (Source: D. Lenka, Department of Agronomy, Orissa University of Agriculture and Technology, 1977, pers. comm.).

The four major river floodplains and deltas in South and Southeast Asia are planted mainly to rainfed rice—the Mekong in Vietnam, the Chao Phraya in Thailand, the Irrawaddy in Burma, and the Ganges-Brahmaputra in Bangladesh and eastern India. Each of these vast rice-growing areas is a complex mosaic of flooding regimes (Kaida 1973).

Shallow favorable ricelands experience a flooding regime sufficiently dependable that semidwarf cultivars are grown and moderate rates of fertilizer are applied. Modern cultivars generally are not cultivated in the other four categories of rainfed lowland rice because they are not adapted to the environmental stresses in these areas.

Crop establishment in the favorable rainfed areas is predominantly by transplanting, as is the case with irrigated rice in Asia. However, broadcasting pregerminated seed on puddled soil (wet seeding) is becoming common in these agroecosystems. On a portion of the rainfed shallow favorable ricelands, the flooding period is sufficiently long (5 or more mo) to grow two successive crops of rainfed rice. Rainfed double-cropping is widely practiced in eastern Bangladesh and in a few areas in Indonesia and the Philippines.

Drought-prone ricelands occupy more than half of the rainfed lowland area. Two major classes of drought-prone environments are recognized (Table 2). In areas where the growing season length is less than 150 d (Class I), a single crop of an early- or very early-maturing, photoperiod-insensitive cultivar is grown. This situation is dominant in South Asia, where the monsoonal rainy period is short. Much of this riceland is broadcast seeded on dry soil prepared before or at the onset of the rains. This practice improves yield stability where the rainy season is very short.

Class II drought-prone ricelands experience lower but highly variable rainfall patterns, which exhibit bimodal tendencies (Table 2). Tall, photoperiod-sensitive rice cultivars are successfully grown in this environment because they are adapted to late transplanting, which is frequently practiced because of the undependable field moisture. This is a dominant agroecosystem in Thailand, where almost 90% of the riceland is rainfed. All of the drought-prone ricelands have a short hydrological year,

Table 2. Characterization of the two subclasses of drought-prone rainfed lowlands (Mackill et al 1986).

Parameter	Drought prone class	
	I	II
Rainy period	Short, monomodal	Long, erratic, bimodal
Characteristics		
Varietal	Photoperiod insensitive, early to very early maturity	Photoperiod sensitive, medium to late maturity
Agronomic	Direct seeded	Transplanted
Distribution	Madhya Pradesh, India; western Nepal; central Burma	North and northeast Thailand; Cagayan, Philippines

limiting the flooding period and the time in which disease vectors would find the fields a conducive habitat.

Submergence-prone ricelands are subjected to unpredictable flash floods, which may weaken or kill the crop depending on their duration. During these short-term floods (10-12 d maximum length), water accumulates because of inadequate drainage or the overflow of river water.

Rainfed medium deep waterlogged ricelands accumulate from 25 to 50 cm of water, which remains stagnant in the fields for a substantial portion of the growing season. Stagnant water may depress growth of the crop due to the highly reduced soil chemical conditions. These areas may remain wet for 6 to 9 mo or more.

Research on a toposequence of sites on the alluvial floodplain of the Cagayan River in northern Philippines illustrates the hydrological relation between drought-prone and submergence-prone, and medium deepwater ricelands common in alluvial landforms of river systems (Fig. 5). Ricelands in the first or highest landscape stratum experienced two prolonged water-deficit periods during the growing season. The second stratum (about 100 m away) at about 0.5 m lower elevation experienced a 70 cm flash flood. The third stratum, a similar distance away from and at a corresponding lower elevation than the second, experienced a 95 cm flood and prolonged medium-deep stagnant water.

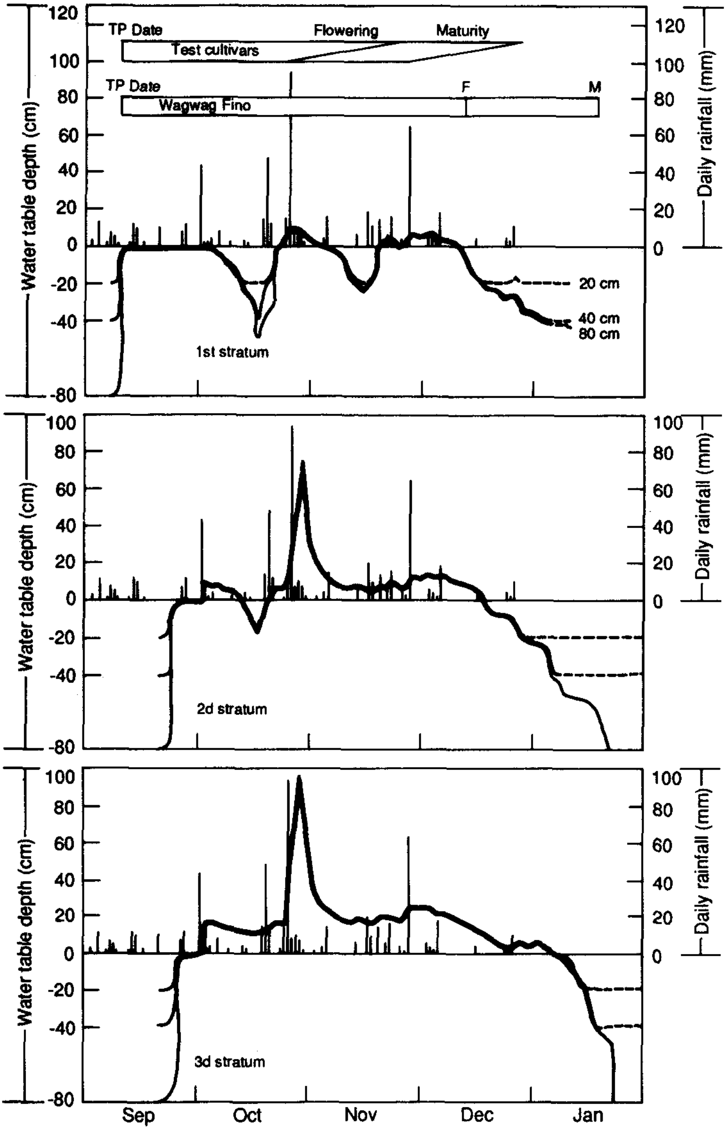
Deepwater rice

There are about 9 million ha of low-lying lands on the floodplains and deltas of the major rivers of South and Southeast Asia where water accumulates and remains for long periods in the rainy season. The flooding patterns on these lands are variable depending on a complex interplay of rainfall pattern, river flow, and floodplain geomorphology. Deepwater areas are defined as those in which the maximum sustained water depth varies from 50 to 100 cm. Tall cultivars, or cultivars that can elongate as the water rises, are grown.

Ricelands with water depth greater than 1 m occupy about 3 million ha in South and Southeast Asian river systems. Some areas are enclosed basins and remain perennially wet. Others, such as those in Bangladesh, are drained by river systems where the water table drops rapidly and deeply when the flooding recedes. Nearly all of the deep and very deep water (and a large proportion of the medium deep water) ricelands are dry seeded before or during the onset of the rainy season.

Tidal wetland rice

The tidal wetlands are rice-growing areas near the coasts that are influenced by daily or twice-daily tidal fluctuation. The amplitude of water depth in the ricefields may vary dramatically on a diurnal and monthly basis. In addition to remarkable heterogeneity in hydrology, these ricelands may be subjected to varying salinity levels from intruding seawater. They include a wide range of difficult soil types, including acid sulfates and peats. The tidal swamps are forbidding environments for human habitation, but settlement of these lands is proceeding in some countries, particularly Indonesia. The area is estimated to cover some 3% of the world rice area and contributes 1% of production.



5. Rainfall and water table hydrograph for different strata on a rainfed lowland rice-growing toposequence, Cagayan, Philippines (Edillo et al 1986).

Upland or dryland rice

More than 19 million ha of rice are grown without surface water accumulation. These may be lands with free drainage (dryland) or with a water table close to, but not above, the surface (hydromorphic). The vector-borne diseases all require standing water for reproduction. Therefore, we would not expect upland ricelands to be associated with disease multiplication.

Rainfed rice agroecasystems and disease vectors

The array of environmental stresses that affect the rice crop in the rainfed agroecosystems reduces the yield potential and returns to higher levels of management, while increasing production risk. Fluctuating, uncontrolled hydrology is a universal constraint on all but a small percentage of the rainfed rice areas. Intermittent soil drying, prolonged water deficits, flash flooding, and deep water are detrimental to mosquito and snail reproduction as well as to rice growth. Two other major factors that have major implication for vector multiplication are the degree of synchrony of planting and the time of rice canopy closure in relation to the time the soil surface begins to flood. Much more needs to be learned concerning the relation between the hydrologies associated with specific rice ecosystems, and the potential prevalence of the vectors.

Rice environmental databases are being developed for Asian ricelands on a regional scale incorporating data on the edaphic, climatic, and hydrologic environment in each microregion (Garrity and Agustin 1986, IRRI 1987). Including information on the environmental factors that relate to the vector-borne disease threat and further interpreting the interrelations may be useful in the management of these problems. Attention should be given to the data required to characterize the rice cultivation-vector relationships on different mapping scales.

Distribution of tropical rice agroecosystems

The distribution of ricelands in the major agroecosystems varies greatly between regions (Table 3). Nearly all rice produced in East Asia (China, Japan, Democratic People’s Republic of Korea, and Republic of Korea) is irrigated, while only one-third of the ricelands in South and Southeast Asia have irrigation. Rainfed lowland rice is dominant in tropical Asia. It occupies the majority of ricelands in five of the countries and exceeds irrigated rice in importance in several others. Future increases in rice production in most of these countries must come mainly from the rainfed lowland areas (Barker and Herdt 1979). Upland and deepwater rices are also important in these countries.

Rice area in West Africa is currently dominated by upland rice (54%), with smaller amounts of irrigated (11%), rainfed lowland (15%), and deepwater (13%) (Table 3). Irrigated riceland occupies nearly one-half of the total riceland in Latin America. There is very little rainfed lowland rice on the South American continent at present, but the potential for expansion in the Amazon basin is large.

Rice area distribution and malaria

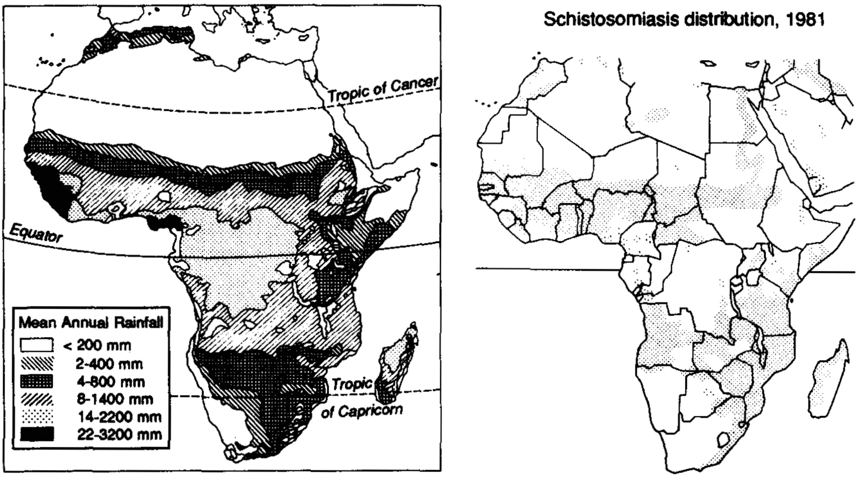
Malaria is endemic in Africa and transmission occurs virtually everywhere rice is grown. There are no major rice-growing areas with limited risk.

The situation is somewhat different in Asia. Malaria transmission does not regularly occur in several of the major river valleys where rice cultivation is densely practiced including the Ganges, Irrawaddy, Chao Phraya, Red River (Vietnam), and Pampanga (Philippines). However, other large areas of rice cultivation in India, Kampuchea, Laos, southern Vietnam, and Indonesia remain transmission zones.

Table 3. The distribution of rice agroecosystems between major regions.

Agroecosystem	Area (%)			
	East Asia	S/SE Asia	West Africa	Latin America
Irrigated	>95	33	11	47
Rainfed lowland	–	35	15	–
Upland	–	13	54	53
Deepwater	–	12	13	–
Tidal wetland	–	5	–	–

- = negligible to nonexistent.

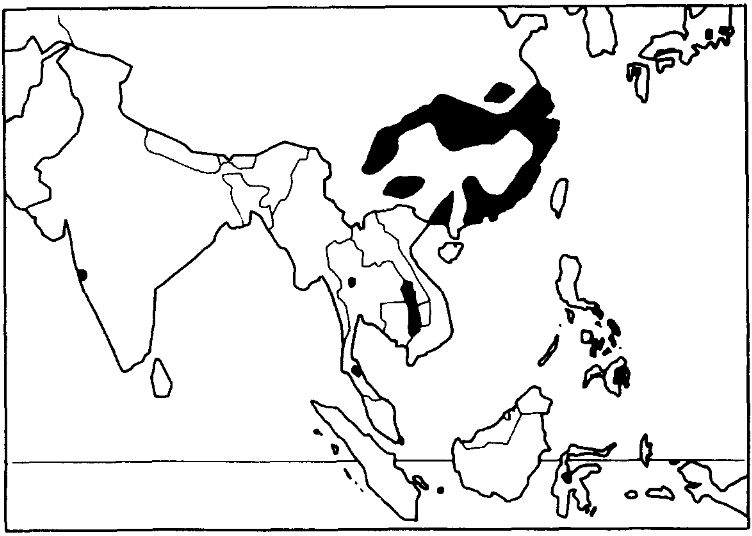


6. Mean annual rainfall in Africa and the distribution of *Schistosoma haematobium* (Grove 1978, Mather and That 1984).

Rice distribution and schistosomiasis

S. haematobium and *S. mansoni* are endemic on most of the African continent where rice is grown. There appears to be a general relation between climatic zones in Africa and the presence of the disease (Fig. 6). Schistosomiasis is generally prevalent where mean annual precipitation is less than 1,400 mm and the growing season is less than about 270 d. In areas where the annual rainfall and growing season length exceed these values, the disease is limited. Long-growing-season areas where the disease is not generally prevalent include the wet forest zones of West Africa and the Congo River basin. It is highly localized in low rainfall areas (<200 mm).

Schistosomiasis is endemic throughout the rice-growing areas of China (Fig.7), the world's largest rice-producing country in which much riceland is double-cropped and remains perennially wet. Outside of China, the disease is not observed in any of the major rice-producing floodplains or deltas of South or Southeast Asia, except in part of the Mekong River valley.



7. Distribution of *Schistosoma japonicum* in Asia (Mather and That 1984).

In the Philippines, schistosomiasis is dispersed across several of the major islands. Its distribution is generally coincident with the geographical extent of the agroclimatic zone with a long growing season in excess of 7 mo with >200 mm rainfall/mo, and a dry season of less than 2 mo with <100 mm rainfall/mo. Thus, the association of *S. japonicum* with high rainfall and a long growing season in the Philippines seems to contrast with that of *S. haematobium* in Africa, which is associated with the less humid environments.

The remarkable geographical distribution pattern of *S. japonicum* in Asia deserves more thorough study. The climatic and rice cultural determinants of its present distribution need to be researched and the ecological factors that have limited its spread better understood.

Trends in rice agroecosystems

Although the demand for rice in Africa is increasing at a rate of more than 5%/yr, the rice production growth rate has been negligible at 0.5%/yr during the past decade. This very modest growth rate was due to an increase in harvested area. Grain yields have actually declined in many countries.

To increase rice production in sub-Saharan Africa, more intensified use of the wetlands is inevitable. Intensive rice cultivation has become a reality on wetlands in some parts of the region despite many technical and socioeconomic constraints. Due to the critical rice shortages now being experienced, methods are urgently needed to expand wetland utilization. However, developing the wetlands will require careful consideration of measures to control the potentially disastrous consequences of the parasitic diseases.

The potential to further develop African wetlands for rice is enormous. Sanchez and Buol (l985) recently estimated the area of wetlands on the continent to be 203 million ha (Table 4). This is 40 times the extent of ricelands currently under production, which cover only 4.9 million ha.

The wetlands in tropical sub-Saharan Africa are categorized as coastal plains, inland basins, river floodplains, and inland valleys. A more detailed inventory of the wetlands by Hekstra and Andriesse (1983) determined their total area at 239 million ha, of which the inland valleys constituted 85 million ha or 36%. These small valleys are widespread in the undulating landscape typical of much of the continent, and are termed dambos, fadamas, bas-fonds, or inland valleys in different localities. Their catchments range from 100 to 2,000 ha and represent an extensive resource for shallow rainfed rice development. Two main types of valleys are recognized: streamflow valleys in the uppermost parts of the river catchments, which receive water from rainfall, runoff, and seepage; and river-overflow valleys further downstream in which the main water source is overflow from the river rather than runoff or seepage. In some valleys, small reservoirs can be constructed to provide year-round irrigation, and this has been done to a limited extent in a few countries. However, most of these lands have never been cultivated, partly due to the presence of water-borne human diseases. Developing the full potential of the wetlands may favor the buildup of large populations of disease vectors and will require careful consideration of control measures from the project planning stage onward.

The land frontier in Asia is largely closed. The difference between area harvested and potential area (Table 4) is accounted for by the large area of peat soils in Indonesia, which have limited scope for development. Therefore, sustained rice production increases in Asia will derive predominantly from higher yield and greater cropping intensity on the current riceland.

Most Asian rice-growing countries have now reached or surpassed self-sufficiency in rice production. International rice prices are expected to remain fairly low in real terms for the foreseeable future. This has reduced the incentive for investment in irrigation development for rice. Expansion in irrigation has slackened, with more emphasis now being placed on upgrading the management of existing systems rather than on building new ones (Greenland and Murray-Rust 1986).

In countries where overall rice self-sufficiency has been essentially achieved, there is now increasing concern with health aspects. The problems of water-borne disease vectors will receive more emphasis as research attention and government

Table 4. The extent of wetland soils and rice area harvested in three developing regions (Sanchez and Buol 1985, FAO 1982).

Region	Wetland soils (million ha)	Rice area harvested (million ha)
South and Southeast Asia	121	90.3
Africa	203	4.9
Latin America	231	8.2

policy shift somewhat from the previous urgent need to provide adequate rice for the population to supporting the development of more stable and sustainable rice production systems.

Greater ecological understanding of the ricefield environment across the range of rainfed and irrigated agroecosystems is essential to evolve an effective integrated approach to vector-borne disease control. Rice scientists and medical scientists should be challenged to work jointly to develop a comprehensive knowledge base on the ecology of vector-environment-management interactions in each rice agroecosystem. The prospect of using environmental management tools as one component of a strategy to alleviate the suffering and anxiety of millions of rice farming families exposed to these diseases is worthy of much more concentrated effort.

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Author’s address: D. P. Garrity, Multiple Cropping Department, International Rice Research Institute, P. O. Box 933, Manila, Philippines.

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The epidemiology of ricefield-associated diseases

D. J. Bradley

The basic concepts of epidemiology are introduced in the context of ricefield-associated diseases. A remarkably high proportion of tropical, especially parasitic, infections are associated with shallow water bodies. Among transient surface waters, ricefields are the world's predominant habitat. Zoonotic arboviruses are transmitted by ricefield-breeding culicine mosquitoes; man is usually a dead-end host and pigs play a major role as amplifying hosts. Malaria is transmitted by anopheline mosquitoes at a wide range of transmission levels as measured by the basic case reproduction rate. In areas of unstable malaria and relatively low transmission, ricefields may provide the only vectors or may greatly increase transmission. Where high levels of transmission of stable malaria already exist, the addition of ricefields and increased anopheline breeding are likely to prolong the transmission season. Schistosomas, especially *S. japonicum,* have strong ricefield associations, but the other species are mainly related to irrigation canals and drains. Many other trematodes have a Southeast Asian distribution, which may be in part due to the long tradition of rice farming in the region. Among the ricefield-associated diseases, only malaria looms large in clinical data, but that is because mild, chronic self-limited diseases are overrepresented in such data. There is great diversity of ricefields as habitats, depending on the proximity of settlements to the fields, the proportion of the land under rice cultivation, and the type of ricefield management as well as the physical environment. This diversity needs to be recognized in the epidemiological aspects of planning vector management.

This introductory paper presents an overview of the epidemiological aspects of ricefield-associated diseases from three directions:

1. The range of tropical diseases as a whole and where ricefields fit into the patterns of disease transmission.
2. The general health and occupational health of rice farmers, and how the vector-borne diseases fit into their disease pattern.
3. The diversity of ricefields in different parts of the world and the implications for disease transmission.

It is possible to view these three approaches as comprising first, disease epidemiology; second, agricultural occupational epidemiology; and third, ecological epidemiology. The third is of particular importance to those concerned with rice farming on a global scale. In setting out these approaches, an attempt will be made to introduce basic epidemiological concepts to those unfamiliar with health work.

The major vector-borne diseases that we associate with ricefields—Japanese encephalitis, malaria, and schistosomiasis—are well known and many aspects of the vectors that determine the epidemiological patterns observed are set out in the other papers in this volume. I will briefly discuss the features of these diseases and some other ricefield-related infections, but concentrate on two areas. First, the variations in epidemiology of the diseases in different places and under varying environmental circumstances and second, the epidemiological questions that remain to be addressed. I hope to suggest new approaches to and ways of looking at the issues that may complement the more orthodox ones.

My main thesis will be the diversity of riceland habitats, the subtlety of epidemiological processes viewed comparatively, and our relative ignorance of long-term secular changes in epidemiology. However, this should in no sense detract from present environmental interventions, since once the epidemiological situation is understood for a specific place—and this is not too difficult to work out—practical control measures are often feasible.

Epidemiological principles

Epidemiological terms

The concept of the denominator, or providing a sense of proportion, is the basic concept underlying epidemiology. Although it is a simple concept, it takes some persons, especially clinicians, a long time to fully grasp its broad implications. Thus, to discuss 373 cases of malaria on an irrigation scheme is clinical medicine. But when one addresses the problem of 387 cases of malaria over a period of, say, 6 mo in a community of 6,300 persons, one is making an epidemiological statement. Then it is possible to compare the risks to those either on different irrigation schemes or between those of different ages or with a different sex or occupation. Many of the technical skills of epidemiology, once the data have been collected, are concerned with allowing for variation, for example, in age. The distribution of the disease in the population and the risk by age may confuse comparisons between different areas. The sense of proportion is thus very much linked to the idea of risk of a particular disease and of the various determinants of that risk or probability. The amount of disease present in an area is usually measured by prevalence or incidence. Prevalence is concerned with the amount of the disease present at a given time. Thus, if we measure everyone's temperature in a village of 50 persons and find that 10 have a fever, then we have a prevalence of fever of 10 and a prevalence rate of 20%. If, however, we consider all those attacked by a disease over a given period, then we have a measure of incidence. Thus, if 10 of 50 persons contract malaria over a year, the incidence rate of malaria is 20%/yr.

The longer an attack or episode of a disease lasts, the greater will be the prevalence for a given incidence of disease. For example, if the incidence of a disease such as influenza is 100% in a community over 1 yr, but on the whole an attack only lasts 1 wk, and if the attacks are evenly spread over the year, only 2% of population will have the disease at any one time and the prevalence will be low. With a disease such as leprosy, which lasts for many years, even a low incidence will in time lead to a high prevalence rate of the infection in the community.

The third useful concept in infectious and transmissible diseases is that of the basic case reproduction rate (BCRR). BCRR is the average number of cases to which one case of the disease gives rise in the next generation of cases among a nonimmune population. If someone with a disease such as cholera comes into a community that has no immunity to the disease, the BCRR will be the number of people in the next generation of cases who catch the disease directly or indirectly from that person before the person dies or gets better. The BCRR concept is useful in practice, because it measures how rapidly a disease will spread. For example, if the BCRR is 2, the number of cases will double in each generation of cases of the disease. If it is 100, then the disease will rapidly increase by a factor of 100 in each generation. The crucial level of the BCRR is 1, because if the BCRR is greater than 1, the disease will spread; if it is less than 1, the disease will die out gradually. For some diseases, such as malaria in areas of unstable transmission, the BCRRvaries about 1; there are epidemics when BCRR rises much higher than 1 and then the disease almost disappears when it falls below 1.

Although the basic concepts of epidemiology are simple, there are many subtleties in the way they are used. With ricefield diseases, although in some ways we are simply thinking of the prevalence of disease in an overall population, we must view the human population as a structured community with a social as well as a biological component, if we are to really understand what is going on. In vector-borne diseases, we must look at the populations of vectors as well, not only in the context of the community but of the community in its environment, that is to say, the ecosystem.

Types of epidemiology

There are many ways of looking at epidemiology. The one most prevalent in developed countries is what Sir Ronald Ross would have called analytical epidemiology. It is the study of disease in populations in order to make inferences about their cause. For example, research workers studied smoking among doctors to come to some conclusions about the possible cause of lung cancer.

The other sort of epidemiology, and one much more relevant to our needs in relation to ricefields, is what Ross called *constructive epidemiology*. That is where all the different aspects of a disease—our understanding of the biology, the sociology, and the economics of the disease in the community—are put together to get an overall picture of the disease, preferably to generate an epidemiological or mathematical model of disease transmission, to work out the best way of controlling it. Constructive epidemiology is a synthesis of many disciplines and requires input from all those concerned with the operation of ricefield agroecosystems, as well as the biologists and sociologists concerned with the transmission and consequences of the disease. It is in these terms that we look at the health problems in relation to ricefields.

Epidemiology has several dimensions. There is a sense in which it is one of the population sciences related to demography crucially, but for vector-borne diseases it also requires firm grounding in the biological sciences and a proper understanding of the biology of disease transmission. Because people are not just biological animals but members of a social structure and a community, the social sciences also are heavily involved. Traditionally, epidemiologists have often lacked a sense of spatial structure in their thinking. Particularly in relation to ricefield epidemiology, it is essential to have a sound geographical background and an understanding of the spatial relations of the components of the transmission cycle of various diseases.

Categories of water-related diseases

The predominant health problems of the Third World are particularly related to communicable diseases and malnutrition. These determine the much greater mortality and morbidity suffered by Third World inhabitants. Particularly in the young, these two aspects interact with each other so strongly that it is difficult to disentangle them.

If we look behind these primary medical etiological categories, communicable diseases are related to two broad variables, poverty and the warm climate. Poverty is a general term, but it is remarkable how similar many of the diseases of the Third World are to those seen in the poorer parts of, for example, London, 100 yr ago. But there is another group of infections specifically dependent on the warm climate. It includes the protozoal and helminthic (worm) diseases, all of which have stages outside the human body. These diseases may be transmitted through insects or other arthropods, through snails, or even through the soil, but those stages outside humans require a warm enough temperature for development to take place. A remarkably large number of the important infections of the tropics are related to water in one or more of four ways. They may be transmitted through drinking water as is the case with cholera and several other bacterial diseases.

Another group of infections is related to the adequacy of water for washing. We have called the diseases in this group the water washed diseases, which include skin sepsis and several of the diarrheal diseases. These diminish when water supplies are adequate for reasonable personal cleanliness. The two remaining categories are even more closely related to surface waters than to water supplies. The first of these may be called the water-based diseases and schistosomiasis is one of these, as is guinea worm. They are diseases that depend on development within an aquatic organism, a snail for schistosomiasis and *Cyclops* (a water flea-like organism) for guinea worm. Infection is either by human-water contact as in schistosomiasis, or by drinking water containing infected *Cyclops* as in guinea worm.

The fourth category is water-related insect vectors. The anopheline mosquitoes, which carry malaria, and the culicine mosquitoes, which carry many arboviruses, have larval stages that develop in water, as do the *Simulium* flies, which transmit river blindness or onchocerciasis. Other insects, particularly tsetse flies, tend to bite near water; humans are particularly infected by sleeping sickness transmitted by the tsetse fly when they collect water.

Communicable and infectious diseases

It is necessary to briefly comment on the classification of communicable and infectious diseases. Those resulting from animal parasites fall into two categories, those due to protozoa and those due to helminths or worms. There are several groups of protozoa and a substantial number are transmitted by insects. The malaria parasites of humans, which belong to the genus *Plasmodium,* are the most important in relation to ricefield diseases.

The worms are classified into roundworms or nematodes and flatworms or Platyhelminthes. Among the nematodes, there are the filarial worms, which cause swelling of the limbs (elephantiasis) or genitalia. These filarial worms are transmitted by culicine and sometimes by anopheline mosquitoes. The filariae that cause river blindness are transmitted by biting flies of the genus *Simulium.* The flatworms are Classified into two groups:

- the trematodes or flukes, a group to which not only the schistosomes but also a substantial number of other ricefield-associated worm diseases belong. All are transmitted through snails, and some have a second intermediate host before getting back to man.
- the cestodes or tapeworms, which usually alternate between humans and other animals but are less directly associated with water.

Among the animal parasitic diseases, perhaps half have water-related vectors or intermediate hosts and they are particularly associated with shallow and transient waters. The other causes of communicable diseases—viruses, bacteria, rickettsiae, chlamydia, and fungi—are less specifically associated with water except those viruses transmitted by insects, most of whose larvae develop in water. These viruses are the arthropod-borne or arboviruses.

When one considers the distribution of shallow and transient waters in the world, there are ponds, marshes, and many other types of seepage. But perhaps the largest area of freshwater in the world comprises ricefields. They are not only large and ancient but also transient. Water flows through them slowly, if at all, therefore they are particularly suitable for many insects and snails. The canals and drains that surround the fields provide many other habitats for disease vectors. In this context it is remarkable how little has been done on the freshwater biology of ricefields and related water bodies.

Diseases in ricefields considered as lesser wetlands

Although several infections are transmitted in ricefields without vectors, for example, leptospirosis, the emphasis here is on vector-borne diseases, which fall into three main categories: viruses, protozoa, and helminths.

Arbovirus fevers

The arboviruses, those viruses transmitted through insects and which actually multiply while in the insect, form a large group of organisms. Many do not produce symptoms in humans, and even among those that do, only a small proportion of people they infect seem to get ill. Most arboviruses are zoonoses; they are transmitted between mosquitoes and a variety of mammals and birds in which the virus persists and survives. Only occasionally are they transmitted to humans, which are often dead-end hosts. Domestic animals sometimes act as amplifier hosts in which the virus multiplies to a substantial degree, often more than in the reservoir hosts normally involved. The greatly amplified quantities of virus may then get transmitted from domestic animals to humans.

There are two main groups of arboviruses—the alpha viruses, which include Onyong nyong and western equine encephalitis, and the flaviviruses, which include Japanese encephalitis and St. Louis encephalitis as well as dengue and yellow fever. The typical zoonotic pattern is seen in western equine encephalitis, transmitted by the mosquito *Culex tarsalis* and maintained in wild birds. From time to time the infection overflows and gives rise to epidemics among horses in the United States and produces some human cases. It is a common arbovirus in the natural system and a rare cause of serious disease in humans.

Yellow fever, although the most important arbovirus in many ways, is primarily an urban disease transmitted by mosquitoes that breed in small containers of water.

The most important arbovirus associated with ricefields is undoubtedly Japanese encephalitis, which has a widespread distribution within the Old World from the USSR to Sri Lanka and east to Japan. The epidemiology varies in different areas, but the disease is usually transmitted by the *Culex vishnui* complex, especially *Culex tritaeniorhynchus*. Again, it appears to be an infection endemic in birds, including water birds such as herons. The virus may then find its way into domestic pigs, which act as amplifying hosts, and subsequently infections may spread to humans.

Large numbers of persons may become infected subclinically, but once a clinical case occurs, the outlook is bleak. Although only 1 of every 500 infected persons may show clinical symptoms, half of those who become ill may die and half of those who recover may suffer long-term, severe brain damage. Prevalence of actual infection may be low, even when incidence is high, because the acute stage of the disease is of short duration. The disease seems to occur in intermittent epidemics, but in several South and Southeast Asian countries, substantial numbers of clinical cases occurred for many years. The important feature is that the vector species seems to be particularly associated with ricefields and breeds there. The relative importance of ricefield breeding and breeding in the water bodies related to ricefields, which are more readily modified, is not entirely clear.

Protozoal diseases

The most important protozoal disease associated with ricefields is human malaria, which may result from infection by any one of four species of the genus *Plasmodium*. Malaria usually presents as a regularly intermittent fever with either 1 or 2 d free of fever between febrile days. The disease may be of disabling severity.

Although the symptoms of initial attacks are usually marked, in those continually exposed to infection the symptoms become milder over time. In highly endemic areas, a symptomless parasitemia is the *normal* state for much of childhood: in holoendemic areas, up to 5% of live-born children may die in infancy.

Malaria caused by *P. falciparum* is by far the most lethal. The infection can rapidly progress to the fatal coma of cerebral malaria, but not always. Mortality in nonimmunes may be very high in the absence of chemotherapy.

The transmission of malaria is much simpler than for the arboviruses because it is a simple two-phase system. The parasites are either in humans or in anopheline mosquitoes. The degree of transmission depends on the numbers of mosquitoes, the frequency with which the particular species bites humans, and the longevity of the adult mosquitoes. Longevity is particularly important because it takes 10 d or more for the parasite to mature in the host mosquito before it can be passed on to infect others. The spread of malaria can be measured by the BCRR, and this may rise to levels as high as 1,000 or more in parts of Africa, although BCRR is only slightly greater than 1 in many parts of Asia. Where BCRR is high and transmission is greatly in excess of that needed to maintain the parasite, the degree of transmission is limited by human immunity to malaria. A further increase in transmission will have very little effect on human health. Similarly, reducing the BCRR from a high level to a lower level confers few benefits.

The anopheline mosquitoes tend to breed in clean water and have diverse habitat preferences. Only a limited number of species are particularly associated with ricefields, and even there the different species flourish at different stages of rice development. For example, in Africa, *Anopheles gambiae* may breed in the early stages of the rice crop, but as the plants develop and cast more shade on the water, *Anopheles funestus* is more likely to breed. Both are highly effective vectors of malaria, but *Anopheles gambiae,* the most effective of all, also breeds successfully in small transient water bodies outside ricefields. Irrigated rice then does not appreciably increase the highest levels of malaria transmission during the year. It may, however, by providing perennial water, change the transmission of malaria from a seasonal process to a perennial one. The effects of this on human disease are complex and not fully understood.

In parts of China, *Anopheles sinensis* is particularly important as a ricefield-breeding mosquito and may be the major vector in several areas. In Sri Lanka, *Anopheles culicifacies,* a major vector of epidemic malaria where the BCRR is usually low, tends to breed in pools formed when streams dry up and may have a complex relation to the use of stream water for irrigation.

Diseases due to trematode worms

The most important trematodes in relation to irrigation systems are worms of the genus *Schistosoma.* There are five main species of *Schistosoma,* all of which have snail intermediate hosts and a four-phase life cycle: one within the human host, one within the snail, and two free-living stages of larval schistosomes in water. One stage goes from the egg, which is passed out in the human excreta, to the snail. The other swims in the water after emerging from the snail and penetrates the human skin.

The cycle is thus much more complex than for malaria and has two interfaces between parasite and human, both of which are determined by human behavior.

One interface is the contamination of water bodies by human excreta, the other at human-water contact that is required for the cercarial larvae to penetrate the skin.

Of the five main species, four are transmitted by aquatic snails. These are *Schistosoma haematobium,* whose eggs are shed in the urine, and *S. mansoni, S. intercalatum,* and *S. mekongi,* whose eggs pass out in the feces. These are therefore associated with irrigation canals, and even more with the drains from irrigation schemes rather than with ricefields themselves.

By contrast, *Schistosoma japonicum,* found in China, Japan, the Philippines, and parts of Indonesia, is transmitted by snails of the genus *Oncomelania,* which are amphibious and found in water and on mud. They particularly flourish in badly tended ricefields. The classical studies of their transmission were conducted in the ricefields of Leyte, Philippines, by Pesigan et a1 (1958) who showed that changing agronomic practices both increased the yield of rice and diminished the suitability of the habitat for snails. Adult schistosome worms, which have separate sexes, live in the blood vessels around the intestine or the bladder of the host. They are long-lived and without treatment, some have been known to live for 30 yr, although a few years is more typical. Persons may be infected by substantial numbers of worms which, as with *Schistosoma japonicum,* lay up to 10,000 eggs/d per pair of worms. A small proportion of these eggs escape from the host through the intestinal wall to be passed out in the feces and give rise to further transmission of the infection.

Most of the disease consequences of schistosomal infection are due to the eggs that do not escape and get swept in the portal blood stream to the liver, where they lodge in small venules. An inflammatory reaction develops, which in turn passes on to fibrosis with multiple obstructions of blood vessels throughout the liver and fibrotic areas. A relatively small proportion of those infected go on to late, severe chronic liver disease with massive portal fibrosis. The patient may die from liver failure or from rupture of the vessels at the lower end of the esophagus brought on by increased blood pressure in the portal system.

In the case of *Schistosoma haematobium,* damage is to the urinary, rather than the intestinal, tract. Fibrosis of the bladder obstructs the flow of urine from the kidneys to the bladder and kidney damage results.

The majority of persons with schistosomiasis get no severe symptoms, although subtle effects such as lassitude and loss of blood and protein with excreta are common. There may be interactions with other infections. If, for example, someone

Table 1. Characteristics of Japanese encephalitis, malaria, and schistosomiasis.

Parameter	Japanese encephalitis	Malaria	Schistosomiasis
Prevalence	Usually low (disease)	May be medium	May be high
Incidence	Usually low (disease)	May be high	Medium
Morbidity	Severe in those affected	Substantial	Moderate
Mortality	Very high	Medium	Uncommon
Disability	Very high in survivors	None	Chronic disease
Treatment	Untreatable	Treatable with difficulty	Treatable
Prevention	Effective vaccine	Chemoprophylaxis possible	No vaccine

with intestinal schistosomiasis contracts typhoid fever, severe fever may continue for many months until the schistomiasis as well as the typhoid is adequately treated.

As with all worm infections, one has to think of infection quantitatively. The chance of severe illness is related to the worm burden of the individual. A person may pick up a few worms from a single exposure to infected water, or many worms as a result of repeated exposure. Thus, helminth infections are quantitative, rather than simply the presence or absence of disease.

The problems related to malaria, Japanese encephalitis, and schistosomiasis differ and although all three are of great public health importance, it is for different reasons (Table 1).

Several other trematode worm parasites related to the schistosomes are distributed in South and Southeast Asia. Their natural history suggests that evolutionarily they may well have been related to rice farming and irrigation systems, although less directly than *Schistosoma japonicum.* These other trematodes are acquired by eating inadequately cooked aquatic foods. Lung flukes of the genus *Paragonimus* pass from snails to freshwater crabs and crayfish to encyst there. *Fasciolopsis* encysts on water chestnut and other edible plants that grow in pools beside or among the rice. Liver flukes of the genera *Clonorchis* and *Opisthorchis* encyst in small fish and infect people when fish sauces made from them are improperly fermented. As rice farming becomes more of a monoculture in a strictly controlled ecosystem, the relation of these infections to ricefields will become more remote.

The rice farmer's health

In most developing countries, the rice farmer is primarily a peasant farmer with limited resources. As with all rural Third World inhabitants, infections are the predominant health problems, with malnutrition and trauma playing lesser but major roles.

The major killing diseases of children will usually be diarrheal diseases and acute respiratory infections. Malaria will be of the same order of importance in the holoendemic areas of Africa, but less so elsewhere, and measles will be far more severe than in the West.

Specific occupational trauma may play a large role in the life of the rice farmer, but there appear to be few quantitative studies. Toxic problems from insecticides may be more common and more severe than has generally been recognized. The ricefield vector-borne diseases show marked geographical variation, depending on the precise nature of the local ricefield breeding vectors and on the availability of nonricefield habitats for the vectors. In Africa, the role of ricefields is likely to be limited in increasing malaria intensity, but important in prolonging the transmission season inasmuch as the key vector has markedly seasonal but extensive larval habitats outside the ricefields. But in areas of unstable malaria, ricefield transmission may greatly raise the incidence of malaria to become a major health problem leading to substantial epidemic mortality, and comparable in its temporary morbidity to major influenza epidemics in the West. Endemic encephalitis increases mortality somewhat. Moreover it increases the burden of dependency in the population by creating a group of brain-damaged members unable to look after themselves and still less able to contribute to community needs.

The ricefield habitat

Ricefields are not homogeneous. There are major differences between the ancient seasonal ricefields of northeast Thailand so well described by Heckman (1979); the massive areas of irrigated rice monoculture of the USA, China, and other Asian countries; the few rainfed rice areas near some African villages; ricefields beside a village in Sarawak; and new irrigation schemes of Western Kenya. This diversity will require collaboration between agriculturalists, ecologists, and epidemiologists to devise an epidemiologically relevant and comprehensible classification of ricefields that will be useful for understanding disease patterns and planning control.

Some important variables are the duration and synchronicity of flooding, which determine vector productivity as well as the degree of turbidity due to disturbance; water depth; temperature; crop growth rates; and crop management. The total area of ricefields will determine total vector production as will the size of the individual fields, because many vectors concentrate at the periphery of the fields. The irrigation methods and channels are clearly important and, except for *Schistosoma japonicum,* the schistosome intermediate host snails will transmit the parasite primarily in canals and drains.

Thus, the engineering design of the system and the agricultural water regimes followed are crucial to both vector ecology and environmental control of the vectors. Peripheral water bodies—balancing pools, ponds and overflows beside sluices, and canals kept full of water for nonirrigation purposes—may all be more important vector habitats than the ricefields themselves except for a few insect species of specialized habitat. These peripheral water bodies are also much more amenable to modification without causing agronomic problems.

A second group of structural variables derives from the location of settlements. A village beside a canal or drain increases human-water contact and will facilitate schistosome transmission. Locating piggeries near ricefields and human settlements, as in Sarawak, places the amplifier host for Japanese encephalitis beside the vector breeding site and increases the chance of viruses being transmitted to humans. Domestic water supplies from the irrigation network reduces contact with schistosomes and biting by vectors near water.

Human behavior interacts with environmental variables to influence disease transmission. Mosquito biting shows diurnal variation, usually with biting peaks around or after dusk. Schistosome cercariae tend to be most prevalent in the water during the daytime; schistosome eggs in urine are most abundant shortly after noon. The occupationally and culturally determined times of humans being in the fields or near the irrigated areas interact with these diurnal cycles of vectors and parasites to define the epidemiological patterns of disease. In the case of arboviruses, the populations and behavioral patterns of domestic stock and wildlife also play a substantial role.

A further set of variables is the existing endemicity of vector-borne infections in the absence of ricefields—a purely theoretical concept in much of Asia but a real one in much of Africa, where the contribution of ricefields (or any other development) to increased malaria levels may be minimal for reasons previously discussed.

Ricefields form a spectrum from the ancient practices in northeast Thailand to the modern, highly managed, commercial ricefields of California. The more traditional agroecosystem is diverse. Crops include not only rice but fish, vegetables, edible mollusks, and fodder for stock. Although many vectors can exist, the complexity of animal populations and predator pressure limits productivity of any one vector. By contrast, strict rice monoculture will have a less diverse fauna, but without intensive control measures, the productivity of a few key vectors may be extremely high. The insecticides needed to manage this situation may create secondary problems.

This inevitably broad review of a large interdisciplinary subject shows the complexity of vector-borne disease relations to ricefield agroecosystems. It should not deter us from looking carefully at health issues in any planned or operating ricefield system, because the local problem will be much simpler than the global one, and only a few pathogens will be of public health importance in the ricefields of any one locality. The problems are tractable and it is usually feasible to reduce vector-borne diseases, but only when the epidemiological situation is first analyzed carefully.

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Author's address: D. J. Bradley, Ross Institute, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, U.K.

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Planning, design, and operation of rice irrigation schemes—their impact on mosquito-borne diseases

K. G. A. GOONASEKERE AND F. P. AMERASINGHE

Irrigation schemes in general provide conditions leading to increased mosquito breeding. Rice irrigation schemes in particular are associated with high incidence of human malaria and arboviral diseases. The planning, design, and operational phases of these systems, with particular reference to the ricefield, are reviewed and the ways in which they contribute to mosquito-borne disease problems are considered. Environmental considerations generally rank well below agroeconomic priorities in the planning of irrigation schemes. Thus the design often does not incorporate features that reduce opportunities for vector breeding. That and defects in construction and subsequent deficiencies in operation and maintenance create vector breeding habitats during water delivery and drainage. The ricefield itself provides opportunities for vector production during various phases of the rice-growing cycle, depending on vector species and cultural practices. The impact on vector breeding of asynchronous cultivation, double cropping, natural manures and agrochemicals, and water management is assessed. While proper planning and design can minimize the risks of vector-borne diseases, many developing countries are faced with the problem of controlling such diseases in poorly designed schemes already in place. The only flexibility left is in operation and management. Attention needs to be focused on operation and management to reduce mosquito-borne diseases in the humans that inhabit these schemes.

Vast irrigation facilities have been developed in Asia during the last three decades (Table 1) to promote lowland rice-based agricultural systems. Large-scale irrigation development has received political, economic, and social priorities as Asian countries have worked to feed their populations and to develop their economies. The majority of them have achieved, or are near to achieving, self-sufficiency in food grain requirements.

Irrigation schemes in general increase mosquito breeding. Rice irrigation schemes in particular have been associated with high incidences of malaria and arboviral diseases. For instance, forest clearing and ricefield extension in the 17th-century U.S. was accompanied by intense breeding of *Anopheles quadrimaculatus* and epidemic malaria, while in Europe, rice growing was associated with malaria in Portugal and Czechoslovakia. Ricefields have led to the proliferation of malaria

Table 1. Irrigated rice area in South and Southeast Asia.

Country	Irrigated rice area (thousand ha)	
	Wet season	Dry season
Island and peninsula countries		
Malaysia	266	220
Philippines	892	622
Sri Lanka	294	182
Indonesia	3,274	1,920
Major river delta countries		
Bangladesh	170	987
Burma	780	115
Kampuchea	214	–
Laos	67	9
Thailand	866	320
Vietnam	1,326	894
Continental diversified grain countries		
India[a]	10,065	2,263
Central	1,590	0
East	3,317	581
North	1,350	0
South	3,808	1,682
Nepal	261	0
Pakistan	1,710	–
Total	20,185	7,532

[a] Only the major rice-growing states of India are represented as follows: Central India: Madhya Pradesh, Uttar Pradesh; East India: Assam, Bihar, Orissa. West Bengal; North India: Haryana, Himachal Pradesh, Jammu, Kashmir, Punjab; South India: Andhra Pradesh, Karnataka, Kerala, Tamil Nadu.

vectors such as *A. gambiae, A. funestus, A. pharoensis* and *A. arabiensis* in Africa; *A. culicifacies, A. aconitus, A. philippinensis* and *A. sinensis* in Asia; and *A. albimanus* in South America. In Afghanistan, new development projects including irrigated rice culture have led to a quadrupling of malaria transmission as ecological changes favored the breeding of *A. hyrcanus* and *A. pulcherrimus,* species that were not prevalent before irrigation. The link with vectors of arboviral diseases is equally clear. Ricefield extension in the Camargue region of southern France resulted in increased breeding of *Culex modestus* and outbreaks of febrile illness caused by West Nile virus transmitted by the mosquito. In California, western equine encephalitis and St. Louis encephalitis are associated with the ricefield-breeding vector *C. tarsalis.* Vectors of Japanese encephalitis such as *C. tritaeniorhynchus* and *C. vishnui* breed most prolifically in ricefields throughout Asia and outbreaks of the disease are commonly associated with intensive rice culture (Mather and That 1984; Reuben 1971; Service 1984; Surtees 1970, 1975).

The dangers of vector-borne diseases related to rice irrigation schemes are well illustrated in recent large-scale irrigation developments in the Mahaweli Development Project of Sri Lanka. Sharp increases in malaria case rates in newly irrigated rice ecosystems within the project have been recorded. In systems B and H, for instance, a fivefold increase in malaria has been recorded from 1982 to 1985. In system C, the malaria rate has virtually doubled over the same period, a particular feature being the tenfold increase in cases of *Plasmodium falciparum* infection in the area (Samarasinghe 1986). In addition, system H saw the outbreak of the first Japanese encephalitis epidemic ever recorded in the island in 1985-86 with 406 reported clinical cases and 76 deaths. Some of the causative factors appeared to be the increased irrigated rice culture in the area leading to high vector densities, increased pig farming, and the movement of settlers from nonendemic areas in the island (Vitarana et al 1986). Increases in the densities of potential Japanese encephalitis vectors are being observed in the developing areas of system C as well.

Summary data on the breeding habitats of some of the important vectors of malaria and Japanese encephalitis commonly associated with ricefields are given in Table 2. Many of these vectors also breed in canals, seepages, borrow pits, etc. that form part of the overall irrigation system. It must be emphasized that when considering mosquito-borne disease problems the ricefield cannot be taken in isolation from other potential vector-generating components of an irrigation system.

In this paper we briefly review lowland rice irrigation systems in general and examine the planning, design, and operational phases of these systems, with particular reference to the ricefield, to consider the ways in which these different phases contribute to the creation and maintenance of mosquito-vectored disease problems.

Rice-based irrigation systems—past and present

Ancient systems

Historically, irrigated agriculture has been a tradition in most Asian countries. Sri Lanka, India, and many others have a heritage of ancient hydraulic societies that have practiced tank-based agriculture for thousands of years. In many of these countries the present irrigation developments have been founded on these ancient works. One signifcant feature of the ancient systems was that they were a network of small units, each of which depended on the vagaries of nature and served a comparatively small population. Another feature was the absence of the application of organic fertilizers and insecticides in agriculture. A combination of good maintenance of tanks and canals and the seasonal flooding and drying cycles may have helped to control vector population increases and held vector-borne diseases in check. In Sri Lanka, for instance, an ancient rice-based hydraulic civilization flourished for 1200 yr from the 1st century B.C. to the 13th century before its eventual decay due mainly to political and administrative disintegration caused by internal feuds and foreign invasions. Although malaria may well have spread to the island by the 13th century, De Silva (1981) emphasizes that that did not cause the abandonment of the rice bowl of ancient Sri Lanka. What is clear is that once the system degenerated, the proliferation of vectors in the abandoned irrigation works led to rampant malaria, which was one of the major obstacles preventing recolonization of much of that area until the present century. In the post-World War II era, the campaign to eradicate malaria by large-scale spraying of DDT contributed much to the success of resettlements in this area.

Table 2. Important vectors of malaria and Japanese encephalitis breeding in ricefields.

Species	Region/Country [a]	Other major breeding habitats
	Malaria	
Anopheles aconitus Donitz	Oriental	Lakes, ponds, swamps, impoundments
A. albimanus Wiedemann	Central and South America, Mexico	Lakes, ponds, swamps, impoundments, pools
A. campestris Reid	Malaysia, Thailand	Canals, swamps, ponds, pools, ditches
A. culicifacies Giles	Middle East, Oriental	Canals, borrow pits, ponds, rivers, streams, pools
A. darlingi Root	South America	Canals, reservoirs, ponds, swamps, pools, stream margins
A. donaldi Reid	Southeast Asia	Swamps, marshes, bogs
A. fluviatilis James	Middle East, China, Southeast Asia	Canals, wells, ponds, streams, ditches
A. funestus Giles	Africa	Swamps, ponds, ditches, lake margins, streams
A. gambiae s.l.	Africa, Yemen	Canals, borrow pits, pools, ditches
A. hyrcanus Pallas	Central and North Asia, Hungary, Japan, Mediterranean	Ponds, swamps
A. lesteri Baisas & Hu	China, W. Pacific	Ponds, swamps, lakes
A. maculatus Theo	Oriental	Streams, seepages, springs
A. pharoensis Theo	North Africa, Middle East	Reservoirs, lakes, swamps
A. philippinensis Ludlow	Southeast Asia	Impoundments, borrow pits, slow rivers, lakes, swamps
A. pulcherrimus Theo	Middle East, Southeast Asia	Swamps, ponds
A. sergentii Theo	Mediterranean, Middle East	Streams, seepages, borrow pits, irrigation ditches
	Japanese encephalitis	
Culex tritaeniorhynchus Giles	Oriental, Africa	Marshes, ponds, pools, ditches, streams, cesspools
C. vishnui Theo. *(syn. annulus* Theo.)	Oriental	Swamps, ditches, rain pools, ponds
C. gelidus Theo	Oriental	Marshes, ponds, pools, streams
C. fuscocephala Theo	Oriental	Rain pools, ditches, marshes

[a] Oriental refers to countries east of Europe and Middle East. It includes India, countries in Southeast Asia and East Indies, and the Philippines. W. Pacific refers only to the easternmost countries of the Oriental Region.

Modern systems

Compared with the ancient systems, the planning, design, and construction of modern irrigation systems have always been on a large scale. The pressing socioeconomic problems arising from population growth and the political objectives of achieving quick solutions to these problems have changed the comparative scale of irrigation development activities. The availability of modern technology and the need to resettle a growing number of landless persons have resulted in massive irrigation systems with large quantities of irrigation water being diverted into water-scarce areas on a scale that has never before been executed. This has been coupled with the use of high-yielding strains of crops, which need frequent inputs of agrochemicals (fertilizers, insecticides) for optimum performance. While socio-economic goals have been achieved, or at the least partly achieved, the consequent impact on the environment has resulted in vector-borne diseases reaching epidemic proportions causing problems secondary to those of irrigation management per se, but of vital importance to the success of the schemes as a whole.

Let us briefly consider Sri Lanka as a case study in modern irrigation systems development. The emphasis on irrigation development, the types of irrigation systems and the consequent problems of irrigation management are similar in most developing countries in Asia.

Planning, design, and operation of irrigation systems

Planning

A feasibility study is normally conducted at the planning stages. However, the emphasis is primarily on the water yields, irrigable area, community resettlement, crops, livestock, costs and benefits, with little or no reference to the impact on the environment. Often, environmental impact studies (including assessments of vector-borne disease potential) are done, but recommendations arising from such assessments generally rank well below political and engineering considerations in the order of priorities. Usually the recommendations get submerged in the cost-benefit debate: The absence of mosquito-borne disease problems in a settler population is a current asset whereas concrete lining of canals to reduce vector breeding, for instance, represents an unacceptable present expense.

In the early stages of irrigation development in 20th-century Sri Lanka, lowland rice was thought to require continuous irrigation during its growth cycle. As a result, the systems were planned and designed with minimum control structures in the main, distribution, and field channels of the irrigation layout, and earth-lined canals were used, greatly reducing the investment required. Major irrigation schemes such as the Parakrama Samudra, Minneriya, Kaudulla, and Kantalai, which were rehabilitated in the north-central dry zone of Sri Lanka, and the more recently built Gal-Oya and Uda-Walawe schemes in the southeastern dry zone are examples of this type of design. In actual operation, however, effective control and management of irrigation water became virtually impossible in such systems. The overuse of irrigation water and the consequent problems such as inequity in water and income distribution, delayed cultivation seasons, and damaged control structures and channels are well documented (Chambers 1975, Goonasekere 1985).

At the initial stages of planning, even the largest and most modern irrigation scheme in the country—the Mahaweli Development Project—followed the same trend. However, more attention was paid to feasibility studies on effective control and management of irrigation water through better design and operation and farmer involvement. At least one feasibility study group had warned of increased incidence of malaria attributed to construction efforts in one of the systems of the Mahaweli scheme (Acres International 1978). The underlying assumption at planning would have been that chemical control of vector-borne diseases would be effective. Environmental considerations received serious attention only in the later stages of development when problems of high water table, drainage, salinity, and epidemics of malaria and Japanese encephalitis were encountered in the earlier systems. If at the planning stages, due consideration had been given the effect of increased water diversion on the water table and drainage, potential vector breeding sources could have been reduced by design and construction and through education and training of the farming communities. However, this flexibility is no longer available with most of the irrigation systems already in place in the country.

Design and construction

Speelman and van den Top (1986) described some of the shortcomings in the design and construction of the Mahaweli scheme, which are equally valid for any irrigation system. They are

- improper elevations of canal beds resulting in stagnant water pools in canal sections;
- erosion from unlined canals leading to silt deposition and the creation of shallow sunlit pools and overflowing canals; and
- seepage from poorly designed and constructed canal sections causing stagnant pools in adjoining depressions.

All are potential mosquito vector breeding grounds. Also, poor quality materials and workmanship combined with inadequate supervision in construction have resulted in fast-deteriorating control structures, which impede effective operation and control and lead to water loss to drainage.

Main system operation and maintenance

With continuous-flow systems, little control can be exerted on irrigation flows due to the absence of control structures (Goonasekere 1985). Operational procedures to provide a uniform and reliable supply of water are constrained by the quality of the design and construction. In system C of the Mahaweli, the accelerated implementation of a complex design in difficult topography has resulted in a complicated operational procedure with consequent shortages or excesses of irrigation water. Often, the lack of written technical procedures for control of flow; absence of explicit instructions to water management staff; poor coordination of policies and activities; and haphazard implementation of rainfall corrections, rotational schedules, and cropping calendars are some of the operational problems identified (Speelman and van den Top 1986). The shortage of maintenance funds can compound the problems caused by poor design and construction, resulting in poorly maintained, silted, weed-choked canals with slow flowing water—ideal breeding grounds for many species of mosquitoes.

Farm-level operation and management

Field channels and farm plots are generally operated and managed by the farmers in all irrigation systems. In Sri Lanka, as in many other countries of Asia, inefficient water utilization at the farm level is a common problem. Use of excess water as a weed control measure, unattended farm inlets, lack of maintenance in field canals, overuse of irrigation water at the head reaches of canals, staggered cultivation due to shortage of farm power, and lack of financial resources are some factors that contribute to waste or shortages of irrigation water at the farm level and to extended cultivation seasons (Chambers 1975, Goonasekere 1985, Moor 1980).

Irrigation in relation to mosquito vectors

Ricelands are classified according to topography and water as pluvial, phreatic, or fluvial. Cultivated rice in most Asian countries is classified as upland/lowland, rainfed/irrigated, and flooded/deepwater systems depending on the hydrology of the ricefields (Mather and That 1984). In general, irrigated lowland rice culture involves a period of land preparation during which the land is soaked. Subsequently weeds are plowed under and the fields are inundated for a minimum of 2 wk before the second plowing which is immediately followed by puddling, leveling, and draining. The crop is established by broadcasting (direct seeded) or transplanting seedlings from a nursery. After seedlings reach a height of 5 cm, the water is gradually impounded to a depth of 3-5 cm. In the continuous submergence system of water management that is the norm, standing water remains in the fields at this depth from the vegetative stage to about 2 wk before harvest. The water regime may differ in other countries depending on the specific cultural practices, e.g., floating rice culture in Thailand.

The reproduction of mosquitoes in ricefields is related to the height of the rice plants, 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 ovipositing, increased shade, and predator establishment in the fields. Mosquito reproduction ceases when the fields are drained before harvest, or may continue at a low level in residual pools. When the broadcast method of seeding is used, mosquito reproduction begins only when the month-old seedlings are flooded, and peaks during the 4-wk postflooding period (Mather and That 1984). Heliophilic species are prevalent during the early stages of rice growth, being gradually replaced by more shade-loving species with the increase in height of the rice plants and canopy development. The pattern of population in the ricefield will obviously differ with different species. Fallow fields flooded before plowing and rice nurseries produce high densities of *A. culicifacies* in India. Subsequent cultural operations such as plowing lead to reduced densities, and the species generally does not occur after the rice plants reach a height of 30 cm (Russell et al 1942). In Africa stagnant turbid water remaining on the fields during plowing can be suitable for species such as *A. gambiae* and *A. arabiensis* (Mather and That 1984). These two species breed at greatest densities during the early stages of rice growth, and are then succeeded during the maturing and mature rice stage by the shade-loving *A. funestus* (Surtees 1970). In China, *A. sinensis* and *C. tritaeniorhynchus* commence breeding after transplanting and density peaks during heading (Pao-Ling Luh 1984a). In Sarawak, immature densities of *C. tritaeniorhynchus* are highest during ripening and after harvest when cut vegetation falling into pools in the fallow fields provides suitable conditions for the breeding of this species (Heathcote 1970). In India, fallow fields and those with rice plants less than 30 cm tall produce mainly *C. vishnui,* while fields with older, taller plants produce *C. pseudovishnui* and *C. tritaeniorhynchus* (Reuben 1971). Asynchrony in cultivation, evident in traditional rice culture, often occurs in irrigation schemes as well, often due to a lack of coordination between farmers and irrigation managers. This, too, can have an impact on the breeding of mosquito vectors. In any given cultivation area some fields may be fallow, others plowed or newly planted, and still others with maturing plants. This could result in the prolongation of the breeding of a vector, as successive ricefields reach the stage suitable for its breeding. In addition, vectors that utilize fields at different rice growth phases could occur simultaneously rather than in the succession that would occur if strict synchrony of cultivation was maintained. Such asynchrony occurring over vast, contiguous extents of riceland could lead to problems of protecting the human population from multiple vectors with different adult ecologies (in particular, biting and resting habits) that complicate control measures.

Traditional rainfed rice culture in much of Asia is dependent on the monsoonal rainfall pattern. This generally restricts harvests to one per year. Modern irrigation systems are devised for double or multicropping to increase rice production, and this has its impact on mosquito reproduction as well. In China, for instance, both *A. sinensis* and *C. tritaeniorhynchus* show a unimodal seasonal pattern of abundance in single rice-cropped areas. In double-cropped areas, however, a bimodal pattern is exhibited, the peaks coinciding with the two periods of rice growing (Pao-Ling Luh 1984a). Thus, there are two periods per year of maximum risk to humans in relation to both malaria and Japanese encephalitis in these areas.

The use of natural manures, fertilizers, or insecticides can significantly affect the mosquito fauna breeding in ricefields. Most anophelines prefer to breed in relatively clean water, but species such as *A. hyrcanus, A. annularis* and *A. varuna* in India and *A. arabiensis* in Africa can survive in polluted water, while *C. tritaeniorhynchus* flourishes in fields containing rotting vegetation (Mather and That 1984). Agricultural pesticides against rice pests also affect mosquito vectors. In some instances, pesticides may have beneficial effects: In Taiwan, for instance, aerial applications of malathion against the rice green leafhopper reduced natural populations of *C. tritaeniorhynchus* and *C. vishnui* 50-80% (Mitchell et a1 1974). Often, however, pesticides may aggravate vector-borne disease problems. In the Ahero scheme of Kenya, applications of organophosphate insecticides against rice stem borers killed virtually all aquatic life in the ricefields. This resulted in a population upsurge of a major malaria vector, *A. arabiensis,* breeding in fields where natural predators had been eliminated (Service 1977). A similar phenomenon was observed in *C. tritaeniorhynchus* in Japan (Mogi et al 1980). Moreover, insecticide resistance in mosquito vectors arising from crop spraying for rice insect pests has been documented, in *A. aconitus* (Java), *A. sinensis* (China), *A. stephensi* (Iran, Iraq), and possibly in the *A. gambiae* complex in Sudan and Upper Volta (Georghiou 1976), thus compounding the problems faced by vector control agencies.

A final consideration is water management at the level of the ricefield. There are basically two types of management for lowland rice cultivation: the widely used continuous submergence method and intermittent irrigation. From an agronomic viewpoint, intermittent irrigation is desirable because of the saving on water. However, the method is not widely used because of constraints such as the need for a complete system of irrigation and drainage, special training of personnel to operate the system, and farmer resistance (Tsutsui 1984). From the standpoint of human health, intermittent irrigation has proved promising. Field trials have shown reductions in larval densities of the order of 75-95% in ricefield-breeding vectors such as *A. atroparvus* in Portugal, A. aconitus in Indonesia, and *A. sinensis* and *C. tritaeniorhynchus* in China (Hill and Cambournac 1941, Mather and That 1984, Pao-Ling Luh 1984b). However, because of the greater intricacies of management and greater costs inherent in the operation of this system, its ultimate applicability will depend on demonstrated reductions in disease transmission (rather than on vector density reductions per se) as well as on rice yields comparable to those obtained by the more traditional continuous submergence method.

Conclusion

Service (1984) makes the point that rice cultivation and irrigation schemes do not necessarily imply an increased risk from vector-borne diseases if proper planning is done to minimize the chances of such problems occurring. However, the primary problem in controlling vector-borne diseases in many developing countries is that the irrigation systems are already in place: planned, designed, and constructed with minimum attention to potential health-related hazards. That gives little flexibility other than in the operation and management area. It is toward this area that our attention needs to be focused most urgently to alleviate the burden of mosquito-borne diseases in the vast human populations that inhabit these schemes.

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Notes

Authors' address: K. G. A. Goonasekere and F. P. Amerasinghe, Departments of Agricultural Engineering and Zoology, University of Peradeniya, Peradeniya, Sri Lanka.

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Planning, design, and operation of rice irrigation schemes: the impact on schistosomiasis

G. WEBBE

In recent years a marked increase in the prevalence and intensity of schistosomiasis in endemic areas has been associated with many man-made water bodies and irrigation projects. Conversion of land to rice-growing may change the general landscape and hydrological pattern of the area, but it does not necessarily lead to schistosomiasis problems. Relatively effective and economical preventive measures may now be possible in water-resource development projects. Simple, rapid, reliable diagnostic techniques to screen residents, migrants, and workers in such developments are available. Those infected may now be treated with relatively cheap and safe oral drugs. To minimize the risk of introducing schistosomiasis into new development project areas, control can be effectively linked to systematic surveillance to prevent the introduction of snails, which transmit schistosomiasis, or to prevent the onset of transmission by existing snail populations. The prevention of unnecessary human-contact with cercaria infested waters is an important component of integrated schistosomiasis control. Rice irrigation scheme planning should always provide for adequate water supplies and sanitation and siting houses away from canals. Surface waters should be protected by covers, pipes, or fencing and facilities provided for bathing, laundering, and water recreation. Storage facilities should have a minimum supply capacity of 48 h duration. Human behavioral patterns, health education needs, and community participation in control must be considered. Problems associated with population movements and resettlements caused by water resource developments are also important. Operational research is required for the engineering and design of water impoundments and irrigation systems to limit snail infestation and for habitat and environmental changes to control snails. Selection of crops, crop rotation, and farming practices may play an important part in schistosomiasis control.

Schistosomiasis is one of the most important public health problems of the tropics and subtropics and is second only to malaria in importance as a parasitic disease. Some 200 million people in 75 countries are probably infected with schistosomiasis and 500-600 million are exposed to the risk of infection. The infection in humans is caused by three main trematode species: *Schistosoma mansoni, S. haematobium,* and *S. japonicum.* Other species may infect humans, including *S. intercalatum, S.*

mattheei, and *S. mekongi,* plus various mammalian and avian schistosomes that do not complete their life cycles in the human host but may cause cercarial dermatitis or *swimmers' itch.*

The disease is distributed widely in Africa and the Middle East (*S. haematobium* and *S. mansoni*) and in the Western Hemisphere in Brazil, Venezuela, Surinam, and certain Caribbean islands (*S. mansoni*). In Asia, China, the Philippines, and Indonesia are endemic areas for *S. japonicum.* Limited foci have also been recorded in the Mekong (*S. mekongi*) and now in Malaya (*S. japonicum*).

Schistosomiasis is predominantly an infection of agricultural and rural communities with some periurban distribution in many countries. Usually, poor-quality housing, substandard hygiene, and an absence of sanitary facilities exist in these places. Children are an important reservoir source of infection in that they contaminate fresh water through indiscriminate urination, while pollution of water with feces as the result of inadequate sewage disposal is a critical factor in maintaining transmission of *S. mansoni* and *S. japonicum.* Schistosomiasis is an occupational hazard for fishermen and agricultural workers in developing countries, but other activities may also result in human-water contact and transmission, including domestic, recreational, and religious practices (Webbe 1981).

It is now generally recognized that the pathological manifestations of schistosomiasis are far more serious than was previously assumed and that the infection may be an important cause of morbidity, especially in adolescents and young adults with consequent disability and profound economic loss (Webbe 1984).

Disease effects of water environments and irrigation schemes

Africa

The number of instances where a comparison has been made between disease distribution and intensity in pre- and post-development situations are relatively few and relate almost exclusively to schistosomiasis. In Egypt, construction of the low dam at Aswan in the early 1930s allowed perennial irrigation in many provinces in Egypt. This was followed by an increase of *S. haematobium* between 1934 and 1937 and levels of prevalence varying from 2 to 11% rose to 44-75% (Khalil Bey 1949). The high dam at Aswan, which produced more extensive perennial irrigation, also changed the schistosomiasis transmission patterns in both Upper and Lower Egypt.

In Ghana, large-scale surveys for urinary schistosomiasis were undertaken over much of the country in the decade before the Akosombo dam was built. Prevalence in children was low (5-10%) around the area that was later impounded. When Lake Volta reached its maximum level in 1968, prevalence was high (90% and more in children 10-14 yr old) in lakeside communities.

Surveys in Mali have also demonstrated high levels of schistosomiasis associated with rice cultivation along the floodplain of the Niger. In the Sudan, irrigation of the Gezira by the construction of the Sennar dam in 1924, and an extension of the irrigation system after 1950, resulted in a progressive increase in schistosomiasis. This also applies to other irrigation systems in the Sudan, including the new Managil extension of the Gezira, the Rahad Scheme and numerous pump schemes along the White Nile, and the extensive transmission associated with irrigation in the west and in the north of the Sudan.

Latin America

Changes introduced by dam construction and other water resource development projects can create or aggravate health risks in different ways. These may be simplified by grouping them into two categories: one in which the ecosystem is fundamentally concerned, the other in which demographic-socio or socioeconomic factors are predominant.

In the San Francisco basin in Brazil there are considerable risks of an increase in schistosomiasis transmission. In the Amazon basin, *Biomphalaria amazonica* is widespread and is now known to transmit *S. mansoni,* thus an increase in schistosomiasis may be anticipated. Migratory movements, population resettlement, and working conditions created by water development projects are other sources of risk, which are predominantly linked to human living conditions (Hunter et al 1982).

Asia

Three main types of water resources development may be found in Asia: multipurpose projects for hydroelectric power, irrigation, and flood control; irrigation projects; and water supply projects. The most important communicable diseases endemic in the region in order of importance are malaria; dengue and dengue hemorrhagic fever; Japanese encephalitis; schistosomiasis; filariasis; soil-transmitted helminths; liver, lung, and intestinal flukes; and cholera and dysenteric infections. All have some potential to spread in water development schemes.

In Indonesia, *S. japonicum* has been found in two small, almost adjacent areas in Central Sulawesi. Unfortunately, they lie close to the only water development project (irrigation) in this island with a population of 9.4 million. Schistosomiasis is not endemic in Malaysia, but one case was found in an aborigine in Penhang State in 1974. Since then, 11 more cases of infection have been detected. A hydrobiid snail, closely related to Tricula, and a rodent reservoir have now been identified as part of the transmission cycle. As in Thailand, there may be a risk of spread of this infection throughout the vast water resources schemes, either in operation or in the planning stage.

Although water development schemes are comparatively recent in the Philippines, an ambitious program is now being developed. Many of the dams already built are solely for generating hydroelectric power and relatively few are for irrigation, but the presence of *S. japonicum* must be taken into account. There is an endemic belt across the eastern and southern islands, southern Luzon, Mindoro, Samar, Leyte, Mindanao, and Bohol, with an estimated 600,000 cases of infection. The threat of extension of *S. japonicum* into the system of dams as the program gains momentum must be considered very real.

In Thailand, the risk of spread of the various parasitic infections must be emphasized, with schistosomiasis being the major potential public health problem in water resources development. *S. japonicum* is not, however, established as an endemic disease in the country. A small focus of infection was found some 25 yr ago in southern Thailand (50 cases), but despite intensive searches, the snail intermediate host was not discovered. *Tricula aperta,* an intermediate host of *S. mekongi,* is found in Ubol Province, but no human infection has been reported (Hunter et al 1982).

Contrast between Africa and Asia

In Africa, schistosomiasis is endemic over much of the populated area of the continent, and its transmission is undoubtedly enhanced by increased human-water contact. Based on available data, the infection clearly constitutes the greatest single immediate threat to health in the development of water resources.

In contrast, schistosomiasis in Asian countries is contained within a few relatively small endemic foci and it has been possible in Indonesia, Malaysia, Philippines, and Thailand to construct large water resources development projects in infection-free areas without introducing *S. japonicum* (Hunter et al 1982). The risks of schistosomiasis becoming established, however, are certainly grave. Houston (1977) predicted that in addition to the existing 50 million ha of land in the world under irrigation, an additional 23 million ha of irrigated land would be needed by 1985—a 46% increase. Thus, human-water contact, vector populations, and disease incidence would rise sharply and appear on a quantitatively greater scale than ever before. Public awareness of schistosomiasis emerges slowly because, apart from certain areas, the onset of the disease is insidious and the appearance of gross clinical manifestations is slow, depending on the intensity of infection. There is a long time-lag between the onset of infection, which can be rapid (within 1 or 2 yr in a new irrigation scheme), and the onset of disabling sickness. Severe cases may not develop for 10 to 20 yr.

Ecology of snail intermediate hosts

Very few distinct relations have been established in snail ecology, and there is a general lack of accurate data. This is due to the euryok character of fresh-water snails and their wide ecological tolerance, which results in less adaptation than most other marine or terrestrial organisms. To a great extent these species react similarly to the same environmental influences—their ecological requirements being qualitatively similar but quantitatively different. Although snail intermediate hosts of *S. japonicum* are amphibious, their responses to differences in physical, chemical, and biological factors in water are similar to those of aquatic mollusks. On land they favor moisture and shade (Webbe 1982).

Bulinid and planorbid intermediate hosts of *S. haematobium* and *S. mansoni* are found in many different habitats, including man-made lakes, irrigation and drainage channels, small water impoundments, and ricefields. The amphibious oncomelanid species inhabit floodplains and habitats resulting from agricultural development—drainage channels, roadside ditches, ricefields, and smaller irrigation canals and drains. Snails tolerate different chemical and physical conditions within wide limits, and usually it is impossible to predict colonization of a particular habitat through chemical analysis of its water. Although snails are sensitive to salinity, it does not always preclude snail survival or disease transmission (Sturrock and Upatham 1973).

The distribution of snail intermediate hosts may be influenced by geological factors, and the snail habitat may be chemically conditioned by ions leached from the related rock formations. The general topography of an area may influence snail distribution. Even though some species are limited by steep stream gradient, in most cases marginal shallows, which can support high densities of snails will occur.

In the Philippines, *Oncomelania quadrasi* occurs only in level regions regardless of other topographical features including elevation. Rainfall cycles affect the life history of snails and determine seasonal fluctuations in their density. This is particularly true of bulinid snails in the tropics and areas with temporary and semipermanent habitats. Intense breeding of planorbid snails has also been reported following seasonal rainfall.

The distribution and growth of snail populations in a given area depend on temperature and other incompletely understood factors. Low winter temperatures in temperate and subtropical zones reduce breeding or stop it completely. Breeding resumes when temperatures increase and snail population densities reach maximum. The general pattern is seen in Egypt in *Bulinus truncatus* and *Biomphalaria alexandrina* and has been recorded with *O. nosophora* in Japan. Temperature is apparently the abiotic factor of greatest importance in determining the distribution of host snails in ponds and lakes. Where rainfall, water level, and temperature are relatively constant, cyclic changes and production may take place throughout the year. *O. quadrasi* showed only minor changes in density over a 2-yr period in the Philippines. There is no conclusive evidence for reproductive and population cycles independent of cyclic fluctuation of environmental factors, but irregular population changes independent of seasonal factors may occur (Webbe 1982).

Most habitats contain rich microflora, which, together with decaying vegetable matter, provide the principal food of snails. Although snails may not prefer any particular species of microflora, the quantitative composition of the diet is probably important in conditioning the habitat. Snails thrive in habitats devoid of higher plant life but rich in green algae, blue-green algae, and diatoms. No causal relationship with a particular species of algae or diatom has been established. *O. quadrasi* has been found to correlate positively with the presence of green algae but negatively with blue-green algae.

That aquatic snail intermediate hosts can survive out of water for weeks or even months has significant consequences in relation to the epidemiology of schistosomiasis and its control. Infection with schistosomes, however, appears to render snails less tolerant of desiccation; immature infections of both *S. mansoni* and *S. haematobium* may be carried in aestivating snails from one wet season to the next (Webbe 1982).

Methods of schistosomiasis control

Chemotherapy

Previously, control measures were aimed chiefly at interrupting transmission as shown by changes in prevalence and incidence of infection. However, following epidemiological research and with the advent of safe and effective drugs (metrifonate, oxamniquine, and praziquantel), control of disease (morbidity) has become feasible, even though transmission may continue at a low level with little or no morbidity (WHO 1985).

Chemical control of snails

During the 1960s, molluscicides provided the only reliable approach to control and dominated most control programs before the advent of safe and effective chemotherapy. The best molluscicide available today is niclosomide, but it has become prohibitively expensive. New strategies of application for focal transmission control and perhaps selective area mollusciciding may, however, provide further economical use of this compound. More adequate strategies and delivery systems are necessary. This approach will play a vital part in the integrated control of schistosomiasis.

Biological control of snail hosts

Biological control has had a wide appeal to field biologists, but as yet no method has been evaluated sufficiently to be recommended or used today. The major constraint to biocontrol in endemic areas has been the lack of a balanced appraisal of safety factors and costs. Suggested methods have included

- competitors such as the snails *Marisa cornuarietis* or *Helisoma duryi;*
- infectious agents, bacteria, or viruses, which infect snails; and
- predators such as ducks, fish, turtles, crustaceans, water-rats, leeches, and aquatic insects.

Marisa, which has been evaluated as a potential competitor in Puerto Rico, has also been observed to feed on rice seedlings. Therefore, its use in controlling snail hosts of schistosomiasis in rice irrigation cannot be recommended (WHO 1984).

Ecological and environmental control measures

Certainly the records of ecological and environmental approaches to schistosomiasis control have been relatively unimpressive, but attention to them has now returned for several reasons.

- Their effect is persistent without continuous reapplication, so that recurrent costs are often lower than for other methods.
- Health benefits may extend to other infective diseases.
- Benefits outside the field of health may sometimes accrue, such as increased agricultural production.
- Evidence of success in controlled epidemiological studies has accumulated.
- Labor and funds are more interchangeable than in mollusciciding or in chemotherapeutic programs.

The approach, which frequently lends itself to local or small-scale use, has also gained support because environmental concern has made people unenthusiastic about chemical control (Bradley and Webbe 1978).

Operational research is required for the engineering and design of water impoundments and irrigation systems, which could limit snail infestation, and for habitat modification and environmental changes, which could control snails.

Environmental design

A marked increase in the prevalence and intensity of schistosomiasis has been associated in recent years with impoundments and irrigation projects in endemic areas. Regrettably, many of these changes were not predicted, nor were any preventive measures introduced at an early stage of planning and development (Brown and Deom 1973).

The development of irrigation for rice cultivation does not necessarily lead to schistosomiasis problems. In Kenya, collaboration between the National Irrigation Board and the Ministry of Health prevented snail infestation in the Ahero pilot irrigation project. This was stimulated by the catastrophic increase in prevalence of infection on the Mwea/ Tebere project in Kenya. In Tanzania, Sturrock (1965) noted that effective and traditional husbandry practiced by the Baluchis kept snails out of their ricefields, whereas infestation occurred in bigger irrigation projects, which were developed for settlement farmers to grow a variety of crops.

It may now be possible to undertake relatively effective and economic preventive measures in water resource development projects. Simple, reliable diagnostic techniques to rapidly screen residents, migrants, and workers are available. Those infected may be treated with relatively cheap, safe oral compounds.

Such control measures can be linked to systematic surveillance against the introduction of snails that transmit schistosomiasis or to the onset of transmission by existing snail populations. The risk of the introduction of schistosomiasis may therefore be minimized in new development projects. Certainly the cost of preventive activities would be relatively small compared to the cost of interrupting transmission, once it has become established.

Human behavior, health education needs, and community participation in control measures must be considered. Although integration of such measures into primary health care may be feasible, particular problems associated with population movements and resettlement caused by water resource developments are also important.

Preventing unnecessary human contact with cercaria-infested water is an important component in any integrated approach to schistosomiasis control. In the environment of ricefields, opportunities for this approach are limited, but in nearby housing and settlements, several measures can be applied. These offer a considerable chance of reducing overall infection levels in the population at risk. In planning a rice irrigation scheme, adequate water supply and sanitation should always be considered.

Housing, water supply, and other facilities

Measures to prevent human-water contact with potentially dangerous waters include siting housing away from canals; providing an adequate, safe water and sanitation; protecting surface water by covers, pipes, or fencing; and providing protective facilities for bathing, water recreation, and laundering. Although drinking water is not a major route of infection, collecting water from infected sources and the related human-pathogen contact is a marked risk. Water storage should always be available with a minimum supply capacity of 48 h.

Water supply

To have any effect on schistosomiasis, more than a basic domestic tap or nearby standpipe is needed (Bradley and Webbe 1978). It must be possible to wash clothes, and it can be expected in tropical climates that children will swim in natural water unless an attractive alternative is provided. It may be necessary to fence off infective streams or pools.

Such comprehensive improvements are expensive and applicable only to nucleated settlements. They have been used in South Africa and in St. Lucia, where there is clear evidence of reduced *S. mansoni* transmission. Although these measures reduce domestic and recreational contact with infected water, occupational contact will remain (Dalton 1976).

The capital costs of piping water to houses vary with the distance from the water source and the settlement density. A system recently installed in St. Lucia costs $7-11/person, including a single tap per household, a community laundry, and a swimming pool. Despite its high capital cost and maintenance, it will confer a general improvement in health with long-lasting effects.

Reducing contamination

The environmental method to reduce contamination is basic sanitation such as latrines. The approach has had a poor reputation, which derives from the work of Weir et al (1952) in the field, and the mathematical models of Macdonald (1965). Latrines, however, are unlikely to control *S. haematobium.* Waterborne sewage systems are too expensive and bore-hole latrines readily become unpleasant to use.

Habits are difficult to change and rice farmers, who spend much of their working day outdoors, are unlikely to leave the field to use latrines. Children and adolescents present the most difficult problem, particularly because they are the most important source of viable schistosome eggs. They are the ones who need health education the most. Only in parts of Asia, where human feces are a valuable resource, is sanitation a really hopeful approach. In China, where night-soil conservation is an established practice, leak-proof storage until ammoniacal destruction of schistosome eggs has occurred is widespread.

Environmental management

The conversion of land into ricefields entirely changes the general landscape and hydrological pattern, which in turn may completely alter the ecology. Although schistosomiasis is predominantly associated with irrigation, natural waters commonly are suitable habitats for snails and are transmission sites in endemic areas. Overflow due to floods and seepage may form marshes, swamps, and pools, which provide additional snail habitats. Human interference in the form of storage, irrigation canals, fishponds, drains, culverts, and crossings often creates a more suitable environment for the snail hosts of schistosomiasis. Snail habitats vary and no single environmental method can eliminate them all. *Biomphalaria alexandrina* in Egypt is most abundant in drains, especially in association with water hyacinth *Eichhornia crassipes,* whereas *Bulinus truncatus* is most abundant in large canals.

Water storage

Large reservoirs are not often a component of the ricefield environment in that they are usually distant from the cultivated area, which is supplied through an existing river system or a conveyer canal or pipeline. Smaller impoundments may typify rice irrigation. For example, night storage reservoirs are used to provide a continuous stream flow for a limited irrigation period during the working day.

Fishponds are another typical impoundment in rice-growing areas, whether operated independently or as a part of the irrigation system. Because they are close to the community, they may have a marked impact on transmission of schistosomiasis. Frequently they serve as aquaria for the snail intermediate hosts (Mather 1984).

Importance of small impoundments

Small impoundments tend to serve more purposes than do large ones. Small multipurpose projects may be used for fishing, water supplies, cattle and livestock watering, irrigation, flood control, etc. Usually the human and animal populations in contact with water are high, with corresponding increase in disease transmission rates. Small dams are abundant in developing countries and in aggregate their significance in agricultural use and in the production of diseases is probably more important than that of large dams. Usually they have no health care measures and the lack of maintenance, seepage control, and water discipline favors the extension of vector habitats.

The irrigation system

Rice irrigation schemes usually provide a variety of aquatic habitats: standing water with or without vegetation, polluted or nonpolluted water, fresh or brackish water, and flowing water. Many of these niches are readily colonized by insect vectors and snails. The presence and degree of disease transmission in a rice-producing community depend on many other factors, including the presence of animal reservoirs for some diseases, the degree of exposure of human populations to the vectors or pathogens, and the presence of parasitic organisms in the population at risk.

Above the diversion structure, the more constant water level and lower water velocities on the margins of the head pond provide an environment suited to snails. These are also the conditions conducive to human use for bathing, laundry, and domestic water collection. These sites frequently provide foci for exposure to cercariae.

Numerous attempts have been made to exclude snails from main canals or to trap them in the upper reaches by screens. Screens have been generally unsuccessful, and, even in pump lift schemes drawing on lakes and rivers, the snails can pass the impellers and survive in the canals (Mather 1984).

Channel design

Snails are rarely seen in streams and canals having average flow velocities in excess of 0.30-0.35 m/s. Snails, of course, cling more easily to a firm, smooth surface such as concrete or stone than to a loose and shifting surface such as silt or loam. Those with conical shells such as *Oncomelania* and *Bulinus* may have lower drag coefficients than snails with flat discoidal shells such as *Biomphalaria.* Aquatic vegetation may shelter snails from the current. As water velocity increases, snails are first immobilized then dislodged. Immobilization itself may adequately control snails where velocity is constant.

An important design note is that it is not the mean velocity in the channel, but the peripheral velocity that dislodges snails. Velocity can be increased by using a smoother surface, for example, concrete, or a steeper gradient. Changing the gradient is largely impractical, because canals must generally follow the surface grade to avoid frequent pumping. The channel cross-section may be made narrower and deeper. Cross-sections are, however, generally designed for hydraulic efficiency—maximum discharge for a given cross-sectional area—since cost is generally proportional to cross-sectional area. In certain soils, velocities high enough to dislodge snails erode the canals.

The effect of water velocities on the infection of animals exposed to cercariae has been studied (Radke et al 1961, Rowan and Gram 1959, Webbe 1966). Infection first increases with increasing velocity then decreases. The velocity of maximum infection is not known, but it is perhaps between 0.3 and 1.0 m/s. It has been suggested that this finding, coupled with knowledge of peak cercarial shedding, may be useful in relation to the use of infected water for bathing and laundry where no other water supply is available.

The role of water velocity in irrigation canals as a determinant of their suitability as snail habitats is well established. The use of water velocity for snail control, however, has probably been unconscious and the serendipitous by-product of factors such as favorable topography and soils. It is too expensive for large-scale use except in irrigation systems where similar velocities would be used (McJunkin 1970).

Canal lining

Canals are lined for many reasons: appearance, public acceptance, weed control, seepage control, erosion control; safety; and reductions in maintenance, size of complementary structures, land required for right-of-way, plant transpiration losses, and total annual cost. Benefits include more water for crops, more land for cultivation, protection of low areas from seepage and waterlogging, and reduction in snails. Hard surface linings have been extremely effective against certain species of snails (Lanoix 1959). Canal lining results in higher water velocities, the relative absence of aquatic vegetation, the potential for rapid draining and drying, reduced seepage to low-lying breeding sites (losses may be 25-50% of all water diverted), and enhanced efficacy of molluscicides, all of which favor snail control (McJunkin 1970).

Of all snail control measures, closed conduits are the most effective (WHO 1965), but probably the most expensive. In Japan, irrigation canals have been lined with concrete and maintained clear of silt, vegetation, and detritus (Komiya 1965). Molluscicides are also used. In addition, chemical fertilizers have been substituted for feces, and this may also have reduced snail populations.

Ricefields have been reclaimed by draining and filling and many have been converted to fruit farming.

As a result, the prevalence of *S. japonicum* has been drastically reduced during the past 25 yr, but at high capital cost. In endemic areas, the use of native cows, which are considered the most important reservoir hosts of *S. japonicum,* is gradually being reduced. Wild rats probably contribute to the maintenance of the disease now.

Piped water and excreta storage are now widely practiced in Japan and many small settlements have swimming pools, all of which reduce the prevalence of *S. japonicum.* Piped water distribution and modern agricultural practices have been successful in many areas endemic for schistosomiasis. The Miwani Estate in Kenya is a notable example (McMullen 1962).

In continental China, the prevalence of *S. japonicum* has been greatly reduced by destroying snail habitats through labor-intensive, low-cost methods. Snails are buried by relining canals or by filling them. When canals are filled, the infective surface layers are buried at the bottom of the channel. New canals are then dug parallel to the old (Mao Shou Pai and Shao Bao Ruo 1982).

Layout and siting

The need to protect the individual from cercarial exposure and the irrigation system from excretal contamination requires siting canals and drains away from settlements. Canals should be constructed at least 500 m away from villages wherever possible. Access to canals should be restricted by closed conduits or physical barriers such as fences. Planned and controlled systems such as these cannot be done by local farmers.

Drainage

Irrigation almost always leads to drainage problems, particularly a high water table and the development of salinity. These are usually controlled by open drains or underground tiledrains. Lack of drainage results in stagnant pools, wet areas, and seepages that are good snail habitats. Drainage flow includes not only excess irrigation water but normal surface runoff, both of which should be determined as a basis for drainage design.

It is uneconomical to line open drains completely. Drains can be lined with prefabricated concrete inverts, which concentrate small flows and increase velocity. The cost of drainage can be surprisingly low compared with the value of land reclaimed and the benefits of increased crop yield resulting from keeping the water table within the desired distance of the root zone. A possible cost breakthrough in drains may be locally manufactured plastic pipe (McJunkin and Pineo 1970). Drainage design, in many rice-cultivation areas, is based on the need to remove excess rainwater or to control flooding within the maximum period of inundation tolerated by the crop at a particular growth stage. The local relief is often level, channel gradients are small, drains are large, and velocities are low. These lead to sediment deposition and weed growth, which is further aggravated by fertilizer runoff from the fields, resulting in an environment ideally suited to many disease vectors (Mather 1984).

This is illustrated by the experience of snail control by mollusciciding at the Mwea/Tebere rice-irrigation scheme in Kenya. Dosing the main canals had little effect on the snail population in the drainage system, which required additional systematic treatment (Choudhry 1974). Where rice is grown under rainfed or seasonally flooded conditions, vector problems may be influenced by the type and standard of drainage. Here, the drains themselves may provide the habitat for a carryover effect of populations between wet seasons. Sturrock (1979) discussed this issue in relation to site modification. In sites that have been modified but not destroyed, it will be necessary to confrm that snail populations have been reduced or eradicated. A single search is not enough if the snail populations exhibited pronounced seasonal variations in density during the precontrol studies. Site modifcation may have altered the optimum season for any residual snails, and populations should be sampled several times throughout the seasonal cycle.

Drainage requirements could be practically eliminated in some areas if conveyance losses were controlled and if water were applied to the land in accordance with soil and plant requirements (Lauritzen 1968). There are few, if any, places where this has been done. Except in places where good natural drainage exists, drains are still necessary.

Intermittent irrigation

The ability of snails to survive in the absence of free water is important inasmuch as channels in well-designed irrigation systems can be dried out periodically. In unlined canals, snails can bury themselves or are stranded on the bottom and survive for several months when irrigation is suspended and the canals dry out. This is especially true in irrigated areas where the groundwater level is sufficiently high to keep the bottom of the canals moist and cool. Clay bottoms, however, do not appear favorable to certain types of snails. It is impossible to level a ricefield so that no standing water remains after drainage. Footprints and other depressions, large or small, inevitably are left in the mud after draining. Therefore it is necessary to wait for 2-4 d for the water in these depressions to dry up or seep away.

It should be remembered that snails have an exceptional reproductive capacity. If a single aquatic snail is introduced into a favorable habitat, it is possible to have a flourishing snail colony in about 40 d and to produce transmission of schistosomiasis in about 60 days. Plants floating in canals or birds may carry snails considerable distances from infested habitats (Luh 1984).

Control of vegetation

Weeds in irrigation canals and drains provide suitable habitats for snails and, where they hamper the application of molluscicides, must be removed. They also reduce the carrying capacities of the distribution system, and the considerable quantities of water they consume reduce the amount available to crops. Weed control is important not only for snail control but also for the proper functioning of irrigation schemes. Mechanical and chemical means are used to control weeds in irrigation schemes. Selective herbicides are usually used for bank weeds and aromatic solvents for aquatic weeds. The number of selected herbicides is continually growing and at least one of them, acroleine (Magnacide R), is lethal to host snails (Ferguson et al 1965).

Trees should not be planted adjacent to canals. Their shade usually is not enough to discourage snail infestations and what shade they do provide may prevent the sun from drying out the canals when they are drained. Moreover, tree roots eventually damage the canal bed and walls, and branches and leaves continuously fall into the water. Much organic rubbish often collects in the water near a lone tree and can stimulate the development of large snail and cercariae populations in the immediate vicinity.

Special structures

Special structures for the proper functioning of an irrigation system and the control of host snails should be included in the system during planning. These include mechanical snail traps, molluscicide-dispenser sites, crossing siphons, flumes, drop structures, shoots, culverts, bridges, division boxes, turnouts, checks, and wasteways. The distribution system should be protected by lateral spillways, drainage inlets, and drainage of natural watercourses over or under the irrigation canals (WHO 1965).

Crop selection

Selection of crops, crop rotation, and farming practices can play an important part in a schistosomiasis control program. If preference is given to crops that do not require large amounts of water, control or elimination of snail habitats is greatly facilitated. Crop rotation makes possible irrigation practices that could prevent snail breeding, especially the amphibious species. Where *Oncomelania* is prevalent, crop rotations can control or even eradicate the snails (Pesigan et al 1958). Crop rotation effectively controls aquatic snails, only where the distribution channel can be dried out as well as the fields. Farming practices could be scheduled so that water could be turned off at suitable intervals to interrupt seasonal fluctuations in snail breeding. Planting or sowing rice in rows simplifies weed control and increases yield, while the attendant cultivation tends to eliminate *Oncomelania* snails in the field. This has been demonstrated in both Leyte, Philippines, and in Japan. The high water requirements for rice and cultivation methods generate problems of snail infestation. Varieties requiring relatively less water should be cultivated. Experiments in Japan showed that, under certain conditions, water applications for rice growing could be reduced as much as 50% without affecting yield. Water reduction can effectively prevent snail breeding in ricefields, drains, and canals if it is consistent with good rice culture. The effectiveness of any of these experimental results for snail control depends on their acceptance and use by the entire farming community (McMullen 1973).

In the Philippines, the number of snails was reduced from 200 to less than 1 / m^2 and rice yields increased by more than 50% in areas where intermittent irrigation replaced ponding (Yoshida 1984, Tsutsui 1984).

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Notes

Author’s address: G. Webbe, Department of Medical Helminthology, London School of Hygiene and Tropical Medicine, Winches Farm Laboratories, 395 Hatfield Road, St. Albans, Herts, United Kingdom.

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The impact of water management practices in rice production on mosquito vector propagation

L. S. SELF AND S. K. DE DATTA

Ricefields are flooded to achieve better growth and yield. Flooding also reduces soil toxicity, restores needed oxygen, and helps control weeds. Water use and moisture stress effects vary at the different stages of growth. The water requirement is low at the seedling stage, but water should be provided immediately after transplanting. Although a large amount of water is consumed in the major part of the reproductive stage, there are times when the fields can be dried to control mosquito larvae. Near maturity, no standing water is required. This paper gives examples of the duration and timing of intermittent irrigation to reduce mosquitovector breeding in Shandong Province, China, and in Japan. Fields can be dried for 2 or 3 d at frequent intervals beginning 2 wk after transplanting. Other control measures, including community participation, are also important to control malaria in the Shandong area. Control measures include moving farm animals outside villages, improving housing structures, screening doors and windows, and using untreated mosquito nets, also nets impregnated with pyrethroid insecticides, and personal repellents. Water management practices to control mosquito larvae must be economical and acceptable to farmers.

Rice is an essential grain that is grown for human consumption in many countries of South and Southeast Asia and the Western Pacific. More than half of the world's population resides in these regions.

The need to grow rice for hungry populations (OECD 1976) normally takes precedence over any disadvantages associated with producing the grain. Health authorities are aware that the vast areas of land set aside for rice growing also provide ample breeding areas for mosquito vectors of malaria and Japanese encephalitis. Both diseases are important public health problems in this area of the world.

This paper draws attention to factors involved in the management of water in ricefields. These topics need to be considered to study and develop an acceptable approach to control mosquitoes and other disease vectors that breed in ricefields.

Water management practices for rice

An adequate water supply is one of the most important factors in rice production. In many parts of tropical Asia, rice plants suffer from either too much or too little water because of irregular rainfall and landscape patterns.

Water management embraces the control of water for optimum crop yield and the most efficient use of the limited supply of water. Proper management of water and irrigation systems, especially those that rely on stored water, enables a water supply during the dry season when yields generally are high due to high solar radiation and greater fertilizer nitrogen response.

Effects of flooding

A main reason for flooding a ricefield is that most rice varieties maintain better growth and produce higher grain yields when grown in a flooded soil than when grown in a nonflooded soil. Water affects the physical characters of the rice plant, the nutrient and physical status of the soils, and the nature and extent of weed growth.

Physical characters of the rice plant. The height of the rice plant is related to its genetic characteristics and to the depth of water in the field; plant height generally increases with increasing water depth. Tiller number, on the other hand, appears inversely related to water depth, at least over a relatively wide range of moisture conditions. With progressive drying of the soil, tiller number decreases, and much more sharply than under the influence of increased water depth.

Culm strength of the rice plant, and therefore lodging resistance, decreases as the plant height increases. Thus, culm strength decreases if culms elongate as water depth increases. There is no evidence that water management practice in the ricefield affects grain-straw ratio.

Senewiratne and Mikkelsen (1961) compared the growth of rice plants in submerged soil and in upland soil. At the early growth stage, rice plants grew larger in the nonsubmerged upland soil than in the submerged soil. Later, however, the plants grown in submerged soil exhibited increased tiller number, greater plant height, and greater leaf area.

Nutrient status, and chemical and physicochemical characteristics of flooded soils. Submerging rice soils increases the availability of many nutrients, particularly P, K, Ca, Si, and Fe. But in a highly permeable soil, nutrients will be leached downward from the root zone. That raises the question of whether internal drainage is desirable; there are advantages and disadvantages.

Internal drainage depresses the concentration of CO_2, Fe, and reducing substances, and prevents the buildup of high concentrations of CO_2, Fe, and organic acids in cold soils. But a disadvantage is water nutrients are lost.

Internal drainage is desirable on cold soils, saline soils, and alkaline soils, and soils irrigated with saline and alkaline water. In the tropics, studies are critically needed to ascertain the benefits of internal drainage in normal soils.

Flooding a soil causes chemical reduction of Fe and Mn, as well as of other elements in the soil. Various organic acids such as acetic and butyric, and gases such as CO_2, CH_4, and H_2S are produced. All except CH_4, when present in large amounts, may retard root development, inhibit nutrient absorption, and cause root rot (usually between the seedling and panicle initiation stages). Toxicity is most often noticed when O_2 in the soil is depleted due to the rapid decomposition of large quantities of organic matter.

O_2 may be brought into the soil by allowing drainage with moderate drying. The reduced substances are then oxidized and the toxic gases may escape through the soil surface. Percolating water can bring O_2 into the soil and leach toxic substances beyond the root zone. Percolation rates of 2-3 mm/d may correct toxicity problems.

Water depth and weed population. Emergence of weeds and the types of weeds in a weed population are closely related to the moisture content of the soil and the water depth in the ricefield. Moist, but nonflooded soil, warm temperatures, and adequate light favor the growth of grasses. In addition, the lack of standing water hinders the effective distribution of granular herbicides, and higher temperature and light may stimulate rapid decomposition of herbicidal components of some compounds.

Water control during early crop growth stages has a major effect on weed control. As weeds become established, it becomes more difficult to control them through water management. For transplanted rice, proper management can substantially complement weeding practices.

Grasses can be completely eliminated if continuous flooding to 16-cm depth is maintained throughout crop growth. Even 5 cm of continuous standing water can substantially control grasses. Infestations of other weeds vary greatly with depth of standing water. Sedges are almost completely controlled by continuous flooding at depths of 15 cm and greater. Broadleaf weed infestation at various water depths is difficult to predict.

Maintaining 10-25 cm water depth has long been practiced in California where water seeding is a common method of stand establishment. However, considerable savings of water are possible if a combination of herbicides and good water management practices is followed.

Types of water loss from ricefields

Water requirement varies among crops. Because rice is semiaquatic, it requires more water than most other crops. Water to produce optimum yields of rice must satisfy the evapotranspiration needs of the crop and losses from the lowland fields through percolation and seepage.

Timely water supply is equally important for optimum growth and high yields of rice. The amount of water required varies with the growth duration of the rice variety, type of soil, topography, etc. Water consumption also varies with the stage of the crop.

The principal moisture losses from the ricefield may be grouped into vapor losses and liquid losses. Vapor losses include transpiration from the leaf surface and evaporation from the water surface. Liquid losses include vertical percolation of free water, which relieves the surface soil and upper subsoil of superfluous moisture, and the runoff of excess water over the field levees.

Water use and drought stress effects at different growth stages

Water use and drought stress effects vary at different growth stages of rice. Sufficient moisture supply is more critical in some growth stages than others. Drought stress reduces crop yield most when it occurs during the critical growth stages.

Water use. It is generally believed that cereal crops show a marked sensitivity to drought stress during the formation of the reproductive organs and during flowering. By and large, cereal crops can withstand and recover from mild or relatively brief periods of drought stress during the vegetative growth period if favorable conditions are quickly reestablished.

With more severe stress, the preflowering stage is the least sensitive and the anthesis and spikelet-filling stages the most sensitive. Matsushima (1962) reported that rice is most sensitive to moisture stress from 20 days before heading to 10 days after heading. Van de Goor (1950) had earlier reported that flooded rice used the maximum amount of water at that time. That suggests that the critical period for drought stress coincides with the period in which plants use the most water.

Seasonal water requirement differs with different growth stages. For water management, the growth stages of rice can be divided into the seedling, vegetative growth, reproductive growth, and ripening stages. In areas with low rainfall or a highly variable rainfall pattern, irrigation practices should be developed to assure needed water at the critical growth stages.

- *Seedling stage.* The water requirement of rice is low at the seedling stage. In fact, if seeds are submerged, the development of radicles is affected by lack of oxygen supply.
- *Vegetative growth stages.* The production of an adequate number of tillers is an important factor in rice yields. Immediately after transplanting, sufficient water should be provided to facilitate tiller production and promote firm root anchorage in the soil. Excessive water at this stage seriously hampers rooting and decreases tiller production. Leaf blades and leaf sheaths of the submerged plants become weak, turn light green, and break easily.
- *Reproductive growth stage.* Reproductive growth starts when maximum tiller production is completed and includes the panicle primordia development, booting, heading, and flowering. A large amount of water is consumed in the major part of the reproductive growth period, which explains why rice is sensitive to drought stress during the reproductive and ripening stages.

  Two factors should be considered for water management at this stage. Drought stress, even for a short period, at this stage causes severe damage and yield loss, particularly when it occurs from panicle initiation to flowering.

  The other factor is excessive water at the reproductive stage, particularly at the booting stage, which decreases culm strength and increases lodging.
- *Ripening stage.* The last phase of the growing period includes the milk, dough, yellowish, and full ripening grain stages. Little water is needed during this period. After the yellowish ripening stage, no standing water is required. This allows draining of a field about 10 d before harvest and facilitates machine harvesting. Rodent damage may increase on drained fields, however.

Drought stress effects at different growth stages. It is generally believed that the peak water demand of rice is between maximum tillering and grain filling stages. In an IRRI experiment on Maahas clay (Andaqueptic Haplaquoll), drought stress imposed at various growth stages was allowed to reach 50 centibars (cb), after which 5 cm of water was added to the plot.

Table 1 shows the grain yield and water use of IR8. Drought stress throughout the entire growth period reduced the grain yield to 20–25% of the yield of the continually flooded treatment. When drought stress was allowed to develop only between the maximum tillering and the heading stages, the grain yields remained relatively high. The reduction in grain yield of IR8 grown on the Maahas clay was more related to the duration of drought stress than to the stages of plant growth at which the stress occurred.

In subsequent greenhouse studies with IR8, IR5, and a traditional variety, H-4, drought stress early in the growth of the rice plant reduced tillering (Table 2) thereby reducing grain yield. If the stress was relieved before the reproductive phase began, some recovery in grain yield occurred through an increase in number of spikelets per panicle. But if the stress period extended into the reproductive phase, a reduction in number of filled spikelets decreased grain yield further.

Moisture stress in the late vegetative and reproductive phases, maximum tillering to heading, and heading to maturity decreased grain yield through a reduction in number of spikelets per panicle, percentage of filled spikelets, and 100-grain weight. Thus, the contribution of panicle number increases with later drought stresses.

Total water requirements. Total water requirement includes water needed to raise seedlings, prepare land, and to grow a crop of rice from transplanting to harvest. The amount is determined by many factors. Those include soil type, topography, proximity to drains, depth of water table, area of contiguous ricefields, maintenance of levees, fertility of topsoil and subsoil, field duration of the crop, land preparation method, and most of all, evaporative demand of the growing season.

Table 1. Grain yield and water use of IR8 grown in tanks with and without bottoms, IRRI, 1969 dry season.

Stress period[a]	Duration (d)	Tanks with bottoms		Tanks without bottoms	
		Yield (g/m^2)	Water use (mm)	Yield (t/ha)	Water use (mm)
None	123	910	618	7.2	1147
T-MT	131	770	653	5.8	1435
T-PI	133	730	632	4.7	1438
T-H	145	720	558	3.8	1121
MT-H	127	880	593	6.3	1178
PI-M	124	760	528	5.9	730
H-M	124	840	544	6.1	904
T-M	152	170	257	1.8	432

[a] T = transplanting, MT = maximum tillering, PI = panicle initiation, H = heading, M = maturity.

Table 2. Yield components of the three rice varieties subjected to drought firms at different growth stages in the greenhouse.

Stress period[a]	Tillers (no./hill)	Panicles (no./hill)	Grains (no./panicle)	100-grain wt (g)	Unfilled spikelets (%)
IR8					
None	7.2	7.2	89	2.55	22
T-MT	4.8	4.4	114	2.57	24
T-PI	4.0	3.9	116	2.52	17
T-H	4.1	3.5	91	2.77	17
MT-H	8.2	7.7	76	2.50	18
PI-M	7.3	6.5	67	2.50	20
H-M	7.7	7.4	79	2.40	34
T-M	7.8	6.2	–	–	–
IR5					
None	8.6	8.5	112	2.67	10
T-MT	5.5	5.4	128	2.63	10
T-PI	4.7	4.7	101	2.63	16
T-H	5.4	5.4	89	2.61	15
MT-H	9.2	9.2	84	2.53	8
PI-M	9.3	9.0	92	2.55	14
H-M	9.5	8.7	109	2.43	16
T-M	4.7	4.2	–	–	–
H-4					
None	8.2	7.6	150	2.57	21
T-MT	4.2	4.1	170	2.73	25
T-PI	4.0	4.0	148	2.60	15
T-H	3.5	3.2	118	2.52	27
MT-H	6.8	6.5	95	2.75	28
PI-M	8.0	7.3	75	2.53	46
H-M	10.9	9.8	69	2.32	53
T-M	3.5	1.4	–	–	–

[a] T = transplanting, MT = maximum tillering, PI = panicle initiation, H = heading, M = maturity.

Rice plants require a large amount of water after transplanting. Field duration from transplanting to crop maturity is generally 90-120 d but with early-maturing varieties, it is reduced by 10-20 d. The amount of water required in the field depends on the water depth maintained, water management practices, soil types, and evaporative demand.

Water requirement in the field from transplanting to harvest is between 800 and 1,200 mm, with a daily consumption of 6-10 mm (Kung and Atthayodhin 1968). In Japan, rice with an irrigation period of 90 d requires 1,000 mm water; rice with an irrigation period of 140 d requires 1,400 mm water. With the introduction of early-maturing modern rice, which matures in 110 d, water requirement is considerably decreased.

Puddling the main field, as opposed to nonpuddling, increases the amount of water used by a rice crop.

Water management systems: characteristics and limitations

The effort required to implement a specific water management practice increases as the amount of water available decreases and as the desired degree of water control increases. Minimum efforts are required for continuous flooding practices, with adequate water supply. These relations do not hold true in areas planted to deepwater rice.

Continuous flooding. Continuous flooding at a static 2.5-7.5 cm depth provides the potential to produce optimum rice yields. Experiments at IRRI show no differences in grain yield between 2.5 and 7.5 cm.

Generally, continuous flooding at 15 cm or more has the potential to produce yields similar to those at 2.5 cm water depth. In some dry seasons, however, a 15-cm depth or more may reduce grain yield.

Continuous flowing irrigation. Continuous flowing irrigation may be useful if irrigation water temperature is high, as in the Kyushu and Shikoku districts in Japan where field water temperature is often as high as 40 °C in July and August. The practice lowers water and soil temperatures, checks abnormal soil reduction, and reduces spikelet sterility. However, it is desirable to reduce the water temperature before water is introduced into the main field.

On the other hand, in Hokkaido, Tohoku, or in intermountain areas in central Japan and in parts of the Republic of Korea, where water temperatures of 25 °C or lower are common, continuous flowing irrigation may increase the water and soil temperature.

In either case, continuous flowing irrigation may increase the availability of soil nutrients. Generally, flowing irrigation will keep the surface soil oxidized, which is highly desirable in strongly reduced soils.

Continuous flowing irrigation has the potential to produce optimum rice yields. For example, in an experiment in Kyushu, Japan, rice yields with continuous flowing irrigation (3-5 cm depth) were generally higher than in the continuous, static submerged plot (5 cm depth) or a water-saving irrigation plot. Water temperature was lowest in the continuous flowing irrigation plot and highest in the water-saving irrigation plot.

At Japan's Niigata Agricultural Experiment Station, flowing irrigation practiced from 35 d before heading to maturity increased yield about 7% over that from the continuous, static submerged plots. But yield was reduced by 8% if flowing irrigation was practiced throughout crop growth, indicating that the period of flowing irrigation may be critical (Matsubayashi et al 1963).

Where water is available in large quantities, the management requirement for continuous flowing irrigation is limited to maintaining the spillway height of the lowland ricefield to control outflows consistent with irrigation inflow rates and the drainage system's capability. Where the water is limited, distribution must be managed to prevent excess water from leaving the productive area. For efficient water use, the water flowing from the lowland ricefields must be recaptured for use on lower fields.

A continuous flowing irrigation system causes some N loss (5-10 kg N/ha) from the soil. If the adjacent ricefield belongs to the same farmer, N will be added there.

Flowing irrigation may not be desirable during herbicide and insecticide applications.

Rotational irrigation. Rotational irrigation is the application of required amounts of water to fields at regular intervals. The field may often be without standing water between irrigations, but ideally the soil does not dry enough for drought stress to develop. Rotational irrigation is often recommended to irrigate a large area with a limited water supply to ensure better equity among water users. A major advantage of rotational irrigation is the more effective use of rainfall in the ricefield.

Rotational irrigation has not been widely adopted because it requires highly trained irrigation personnel as well as good farmer cooperation. Conveyance systems must be equipped with additional structures such as division boxes and flow-measuring devices, and weed growth is greater when the plots lack standing water for a time. Water requirements for typical designs in Taiwan, China, vary between 1,000 and 1,300 mm with a moderate level of irrigation management within the system and on the farms. With effective water management, satisfactory yields were obtained with 650 mm delivered to the farms.

Midseason soil-drying. Japanese farmers practice midsummer soil drying or midsummer drainage of the ricefield. The primary benefit in Japan is that the root zone is changed temporarily to an oxidized state, which in some cases prevents root-rot disease. Removal of anaerobic toxins and CO_2 is a distinct advantage of midseason drying of some soils. Another advantage is that nutrient supply to the crop, particularly N, at later stages is regulated to suppress the growth of late tillers. Some irrigation water may be saved, but where water supply and control are poor, as in the Asian tropics, midseason drying may subject the crop to undue drought stress. Other disadvantages include possible root pruning caused by soil shrinkage, the reversal of beneficial pH changes, and increased N loss.

Midsummer drainage is done late in the tillering stage, before early panicle formation. At that stage, the number of panicles is fixed and the water requirement by the rice crop is minimal. However, when physiological disease symptoms such as sheath rot occur earlier than the late tillering stage, water should be immediately removed from the fields or at least reduced.

In Japan, midsummer drainage is advocated in soils in which rapid soil reduction occurs and in which excessive fertilizer N, which delays ripening, should be removed by rapid oxidation at the late stages of rice growth.

Water management between crops. To increase production of crops planted after lowland rice, we need to understand more clearly the drainage pattern during the transition from the wet to the dry season. Soil water drainage and water table recession rates after lowland rice harvest in the wet season have obvious implication for rice-based cropping systems (Klodpeng and Morris 1984).

The choice of water management practice between crops is largely determined by the farmers' objectives. The choice is mainly between dry and flooded fallow.

Dry fallow is commonly practiced in most rice-growing areas. Drying the soil between crops saves water and hastens ammonification on reflooding. The disadvantages are reversal of reduction and loss of about 40-80 kg N/ha per season.

With flooded fallow, standing water is maintained between crops. The advantages are favorable chemical environment, reduced N loss, and accretion of about 150 kg N/ ha per year. The disadvantages are high water use; accumulation of organic substances, salts, and alkali; and an increase in zinc deficiency.

Rainfed. More than 50% of the world's rice-growing area depends on rainfall for water, with rice grown mostly in rainfed bunded fields. Good water management is highly important for raising rainfed lowland rice production in South and Southeast Asia. If water supply to the crop is adequate, yields will be similar to those of irrigated rice.

In the Philippines, where 41% of the total cropped area is rainfed, some farmers store rainfall and runoff water from adjacent fields in ponds built on the farm. They use the stored water to supplement rainfall in the ricefields during the wet season and to grow a second irrigated rice crop in the dry season. Farmers also grow fish in the reservoirs (Moya et al 1986).

Rainfed varieties are generally taller (130 cm) than semidwarf varieties grown in irrigated fields. If there is stagnant water 30-50 cm deep in rainfed fields, the intermediate-statured rice has the best chance to produce 2-3 t/ha.

Rainfall of 900-1,000 mm during the growing season is adequate to produce optimum yields with moderate levels of water management. Where normal rainfall exceeds 1,500 mm, which is fairly common in most of Southeast Asia, and is reasonably well distributed throughout the growing season, relatively little management is practiced unless surplus water accumulates in a field. Sometimes drainage may be needed to eliminate excess water.

Where the normal rainfall is about 1,000 mm or less, and distribution is often uneven, as in most of South Asia, careful water management must be practiced. Bunds must be carefully maintained to minimize seepage and surface drainage losses. Higher bunds, carefully maintained, allow greater depth of water to be retained in the lowland ricefields.

Water management practices for continuous cropping

With increased demand for all food crops, particularly rice, efforts to raise total food production have been increased. One way to achieve that is to increase cropping intensity. Good water management is an important prerequisite to increasing cropping intensity.

Continuous rice cropping. When adequate and assured water supply is available, continuous rice cropping with at least three crops a year is possible where year-round favorable temperature provides that opportunity. Experiments suggest that continuous flooding is not essential for high grain yield but modern rice varieties can tolerate at least 15 cm of water without reducing grain yield. In an IRRI experiment, yields on continuously shallow flooded plots were similar to those on plots continuously flooded at 10-cm depth. Deeper submergence has other advantages, however, such as weed suppression, higher fertilizer efficiency, and better insect and weed control with granular chemicals. Considering all factors, continuous submergence in 5-7.5 cm water is probably best for continuous cropping of irrigated rice. In zinc-deficient soils, drainage is between crops and, in extreme cases, drainage during early rice crop growth is highly desirable.

Rice-based cropping systems. It is becoming increasingly evident that continous year-round rice cropping is often undesirable, even where there is adequate water. Growing other crops in rotation with rice means a large increase in nutritional and economic benefits. In addition, rice pest pressure is less under a good rotation system.

In heavy-textured soils, however, it is difficult to switch from puddled soil to nonpuddled soil, which is essential to grow an upland crop. Strong arguments have been presented for furrow-irrigating rice on nonpuddled soil as an alternative to puddling soil for rice cultivation. Maintaining the soil in a nonpuddled or dryland condition allows the ready insertion of other crops into a rotation centered on rice.

Research data (IRRI 1971) show that more than one-third of the water involved in evapotranspiration is from the surface of the standing water in a ricefield. Thus, furrow-irrigating a nonpuddled soil might lower the requirement of the rice for irrigation water. Evaporation from the field would be retarded by the mulching effect of the dry surface soil. Deep percolation losses could also be reduced. The importance and benefits to be derived by reducing the irrigation requirement of rice have been discussed by Young (1970).

Water management in direct-seeded flooded rice

In the Asian tropics, rice is primarily transplanted for stand establishment. However, in most of Sri Lanka, and in parts of India and Bangladesh, rice is broadcast-seeded onto dry soil or wet or moist soil. Wet seeding on a puddled field has become an important stand establishment system in Malaysia, Thailand, and the Philippines (De Datta 1986).

Seeding into standing water is uncommon in the tropics because of the lack of proper water control and because low O_2 concentration in water under the high tropical temperatures lead to poor stand establishment. Evidence suggests, however, that broadcast seeding into water is a distinct possibility if proper water management can be provided.

In an experiment at IRRI, crop establishment decreased as the water depth was increased for direct-seeded flooded rice. A brief drainage period at maximum tillering and panicle initiation reduced lodging, but increased weed populations.

Case study on rice growing and malaria vector control in Shangdong Province, China

The information in this section was obtained during the visit of a World Health Organization team to China in July 1981 (Self et al 1981).

Malaria situation in Shangdong

Malaria is the third leading cause of morbidity in Shangdong Province, after acute respiratory infections and diarrheal diseases. *Anopheles sinensis* is the only vector of malaria in Shangdong, and falciparum malaria does not occur. The main reason for continued malaria transmission, despite control efforts, is increased rice production.

The province is situated in the lower reaches of the Huang River, with its eastern and northern borders facing the Huang and Pohai Seas. The southern part of the province consists mainly of plain areas.

Transmmission, climate, and population. The annual mean temperature is 16 °C. The mean monthly temperature peaks in July (27 °C). Annual rainfall in the south is 800-900 mm. About 70% of the total yearly rainfall occurs in July and August. The main crops in the south of the province are rice in summer and wheat in winter. The dry farmland, which prevailed in the past, has been transformed into ricefields by extensive irrigation schemes which were begun in 1958.

Malaria is transmitted by *A. sinensis,* and is characterized by high instability and frequent malaria epidemics, whenever the natural conditions and other factors favor transmission. *Plasmodium vivax* is the only parasite responsible for the disease. The relative humidity during the transmission season is more than 70%. Malaria incidence in the province was low in the past, but started to rise in 1959 as a result of extensive irrigation and increased rice production areas. Anti-malaria campaigns have reduced the annual parasite incidence from 50 cases per l000 persons in 1971 to 12 per 1000 in 1980. The main factors that favor the transmission of malaria are

- optimum temperature and humidity,
- high density of mosquitoes breeding in vast ricefield areas,
- exophilic nature of the vector, and
- the existence of *P. vivax* strains of prolonged latency that can bridge the gap between two transmission seasons.

The transmission season is from June to October. There are usually two malaria peaks; the first one in May-June represents relapses or cases of prolonged latency, and the second in August and September is due to recently infected cases with a short incubation period.

The houses are congregated and well constructed from mud, mud bricks, or mortar bricks. The inside walls may be lime washed or covered by paper. There are usually no windows facing the north, or there may be one small window with poor ventilation. The average population per house is five.

Animal shelters are either attached to houses, exist as a separate entity within the village, or are located outside the village. In areas with high mosquito densities, more than 90% of the population use mosquito nets. The population does not consider malaria a serious problem, but is more concerned with mosquito bites. Residents burn rice straw mixed with HCH to repel mosquitoes at night.

Workers usually arrive home from the field about 1900 h. They may stay outdoors until 2100 h and then retire indoors. Some, however, prefer to sleep outdoors.

The ratio of inhabitants to cattle can be 16:1, but it varies according to locale. The average farmland per family is 0.5 ha. Men and children commonly wear sleeveless shirts in the summer.

Villages in the plain area are situated amid ricefields, in which the water depth at the time of the team visit was 5 cm or more. Farmers rarely use insecticides for rice production, and use herbicides once at transplanting. Generally speaking, the population appears healthy.

The vector. The principal vector of malaria, *A. sinensis,* breeds in relatively clean, standing water with vegetation. The main breeding places are ricefields and small irrigation and drainage ditches. The vector is also found in small pools, grassy fields, reed ponds, and ditches in the vicinity of villages. In dry farmland, the breeding sites are ponds, canals, ditches, marshes, and low-lying land with standing water. Breeding also occurs in lakes overgrown with weeds.

In the rice-producing areas, larvae first appear in late April and early May in ditches around villages. They are also found in the rice seedbeds in early June about 2 wk before transplanting.

Overwintered adults first appear in March and are found in cowsheds. After oviposition, the first-generation adults appear in mid-May, with the density remaining low until June. The density increases in July and peaks in August and September; thereafter it declines with the last detected adults disappearing from animal shelters in December.

During the peak season, A. sinensis bites throughout the night, with most of the activity occurring 2-3 h after sunset. Although it is highly exophilic and zoophilic, appreciable biting densities can occur on humans when the densities on cows are high.

Precipitin tests of blood-fed specimens collected from outdoor resting places show that 90% feed on cows, horses, pigs, and sheep, with about 10% feeding on humans. Pigs are nearly as attractive as cows, with each representing about 25% of the total catch.

A. sinensis mainly rests outdoors during the day in widely dispersed sites, which include shrubs along irrigation channels, shaded vegetation on the periphery of ricefields, and straw heaps within villages. A few specimens can be found in well-constructed cowsheds, which are not well-ventilated. The species is rarely found resting inside houses during the day.

Females naturally infected with sporozoites are rare; normally, several thousand specimens need to be dissected to find a positive one. Only about 15% of 900 mosquitoes that were fed on malaria patients had sporozoites in the salivary glands.

The optimum temperature for the development of sporozoites is between 25 and 30 °C. The time required for their appearance in salivary glands at 19 °C is 23 d and at 28 °C, 7 d. The gonotrophic cycles are 4 d at 19 °C and 2 d at 28 °C. Thousands of specimens collected from animal shelters during the peak season had an overall parous rate of 50% and a theoretical daily survival rate of 82%.

Although most of the above factors indicate that *A. sinensis* is not a good vector for the transmission of malaria, the vectorial capacity obviously increases under optimum temperature, permitting the parasite to rapidly develop in the mosquito, while at the same time allowing this species to quickly complete its gonotrophic cycle and take more frequent blood meals. This results in a high vector population with greater risks for humans being bitten by infected mosquitoes.

Hibernating adults have been found in cowsheds, straw heaps, caves, and underneath bridges. There are some indications that strains differ in their degree of exophily and zoophily in different areas of China, but this subject requires further study. The flight range of *A. sinensis* can be 2 km or more.

Agriculture. The rice-farming areas in the southern part of Jining region in Shangdong County used to be swampy, subject to frequent flooding and locust invasion. Only one crop of wheat or other grain was possible, with a low annual yield of about 1.5 t/ha. After the construction of the multipurpose South-Four-Lake project and the many drainage-irrigation stations in the area in the mid-1960s, a large amount of land was converted into ricefields where one crop of irrigated rice and one crop of wheat are grown annually. Average annual rice yield is about 4.5 t/ ha and wheat yield about 3.0 t/ ha.

Tongkou Commune is comparatively more fortunate in the availability of water, because it is located along the Zhao Wang River, which eventually connects with the Nan Yang Lake of the South-Four-Lake project. Of a total 6,000 ha of cultivated land, 4,600 ha are ricefields. The population in the commune is 70,000. The Fan Li Zhuang Brigade, of the Tongkou Commune, has a population of 890 and a total cultivated land area of 104 ha, of which 90 ha are ricefields. In this brigade, the annual rice yield is 6-7.5 t/ha and wheat yield about 4.5 t/ha. These figures generally reflect the overall picture of the commune.

Irrigation and drainage. The purposes of the South-Four-Lake project are irrigation, flood control, drainage, and navigation. The construction of an earthen dam across the narrow stretch between the Zhao Yang Lake and the Weishan Lake increased the storage capacity of the upper portion of the lake to 800,000,000 m^3. This quantity of water, together with the available flow in the various rivers in the watershed, provides the source of water for irrigating the ricefields in the southern part of Jining region.

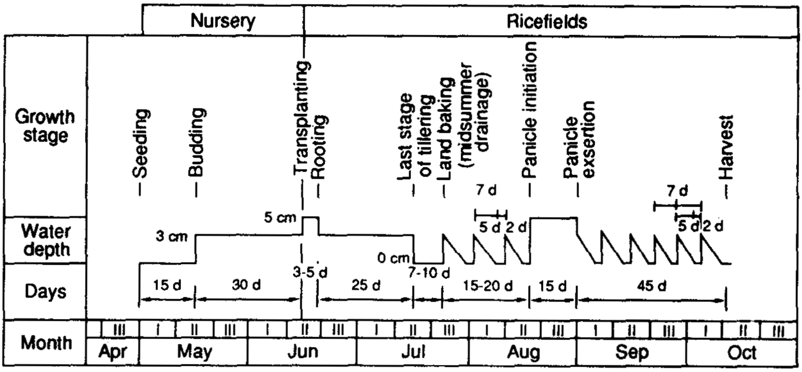
The lakes are located in the lowlands and water is pumped to the level of the main irrigation canals.

The irrigation canals and drainage ditches are classified by size as mains, branches, ditches, farm laterals, and capillaries. A simpler layout is adequate in most situations and therefore not all sizes are present in all systems.

Some irrigation canals and drainage ditches are located parallel and adjacent to each other; others are separated. An advantage of the former arrangement is that material excavated from the drainage ditch is used to build the embankment of the irrigation canal. The small ditches, in particular those of the capillary category, are often used for both irrigation and drainage. The irrigation canals and the main drainage ditches were reasonably well-maintained and generally free from vegetation, although considerable weed growth was found in the smaller ones.

Because of the importance of ricefields to *A. sinensis* breeding, the irrigation schedule for rice farming has received special attention. Whereas the old irrigation method was to keep the field flooded continuously until harvest, except for a short land-baking period, the present procedure, used since 1977, is intermittent irrigation during two specific periods of rice growth (Fig. 1).

Reports indicate that the new irrigation procedure has increased yield remarkably. However, the drying periods were not sufficiently long to allow the land



1. Ricefield cropping calendar, Tangko Commune, Shandong, China.

to be completely dried to ensure destruction of mosquito larva. Further studies are required to improve intermittent irrigation to enhance its effectiveness for mosquito control.

Environmental management control measures

Environmental management measures have been used extensively to improve the living standard of the rural population in the village rebuilding program in Jiaonan County, which involves an area of 1,880 km^2 and a population of 768,400. The plan includes a scrupulous preparation of village sites and grading and filling to ensure efficient drainage to eliminate numerous mosquito breeding sources. New houses are situated in rows all facing south. All have improved ventilation, and the higher quality construction helps to reduce human-mosquito contact. Trees are planted along major streets and cattlesheds are located outside the villages. To date, 80% of the villages in the county have been improved in varying degrees.

The Wang Zhia Chun Brigade of Haiya Commune is an example. Before rebuilding, it was reported that ditches of dirty water crisscrossed the village and water pools were abundant. By grading and filling, all such natural depressions were eliminated and two large ponds of stone masonry were constructed, one at each end of the village. These receive rainwater runoff and fish are cultured in them.

A total of 1,100 old rooms were demolished and 1,600 new rooms were built for the total brigade population of 1,505. There were 73 malaria cases in 1972, 1 in 1975, and none since 1976.

In addition, in Jiaonan County, reservoirs, wells, pumping stations, irrigation canals, and drainage ditches have been constructed, water courses straightened, and river banks improved. The swampy conditions of Jiaonan County have been remarkably modified and the chances of flooding greatly reduced. Mosquito breeding is reportedly much less now than in the past.

In Jining area, intermittent irrigation is practiced during two periods of rice growth. But the drying of land between flooding is not sufficient to destroy mosquito larvae. The ricefields are kept flooded from transplanting until the last stage of tillering (from mid-June to mid-July). That provides favorable breeding sites for mosquitoes and is probably the major cause for the peak density of *A. sinensis,* which begins in late July or early August.

In principle, the modified irrigation practices suggested should not reduce crop yield, but result in saving water.

The first modification is to slightly extend the drying time during the two periods when intermittent irrigation is being practiced (from 20 Jul to mid-August and from early September to mid-October). The present practice involves flooding once every 7 d. The water applied is left in the fields to be dried by evapotranspiration and percolation, resulting in a 5-d wet and 2-d dry cycle. Reducing the quantity of water applied by 15-20% would create a cycle of 4-d wet and 3-d dry. When it rains, water in the fields should be drained, if necessary, to ensure the 3d drying period.

The second modification is to begin intermittent irrigation 2 wk after transplanting and continue it until the land-baking period (from early to mid-July). Intermittent irrigation has been practiced in the wet irrigation experiment in Henan Province, without any reported rice yield reduction. However, this part of the trial must be carefully observed because the suggested modification reflects a more significant change in the present irrigation practices.

In Henan Province, wet irrigation has been tried to control mosquitoes with promising results. The method involves a 5-d flooding-drying cycle for the entire growing season, except for the 2- to 3-wk period after transplanting. The soil in the experimental area is sandy, and the wet irrigation method saturates the soil without surface flooding. That prevents mosquito immature stages to complete their development. Extended use of this method is to be encouraged. In clay soils, percolation is slow and the wet irrigation is difficult to use with success. Based on the experience in Japan, intermittent irrigation is possible except for a few growth stages of rice (Table 3).

Intermittent irrigation is being practiced in the Jining area to increase rice yield but not as a mosquito control measure. The present practice may have only marginal effects on mosquito breeding and needs to be modified to enhance its effectiveness.

During the early period after transplanting, fields are flooded not only to meet the high water requirement for rice growth but to control weeds. As the rice grows, the water requirement decreases, and the land-baking process takes place when the requirement is at its minimum. The ricefields should be completely dried, so that cracks of 1-2 cm show up on the land surface. Drying promotes root activity, provides O_2 to the soil, releases harmful gases (notably H_2S), and removes soluble Fe by oxidation. Intermittent drying in an intermittent irrigation practice will provide these advantages, too.

In Nanxiang area of Jiading County, Shanghai, workers of the Anti-Epidemic Center routinely clean small irrigation and drainage ditches and apply larvicides. There are plans to involve the community in this work.

Conclusion

Various factors involved in the management of water in ricefields need to be considered in developing a suitable vector control approach. If environmental and water management practices are to be used to minimize vector breeding, the

Table 3. Water requirements in Japanese ricefields and opportunities for vector control.

Calendar age (assuming transplanting on 10 Jun[a])	Growth stage	Water necessity[b]	Remarks
10-20 Jun	Transplanting	MN	Intermittent irrigation impractical
21 Jun-1 Jul	Rooting	MN	Intermittent irrigation impractical
2-12 Jul	Primary effective	N	Intermittent irrigation possible
13-23 Jul	Secondary effective tilling	N	Intermittent irrigation possible
24 Jul-3 Aug	Noneffective tilling	LtN	Can be dried for vector control
4-14 Aug	Ear-primordia tilling	N	Intermittent irrigation possible
15-25 Aug	Ear-sprouting	MN	Intermittent irrigation impractical
26 Aug-5 Sep	Heading/flowering	N	Intermittent irrigation possible
6-16 Sep	Milky/dough	N/LsN	Intermittent irrigation possible
17-27 Sep	Yellow ripe	LsN	Intermittent irrigation possible
28 Sept-8 Oct	Full/ripening	LtN	Can be dried for vector control

[a] Each growth stage is assumed to be 11 d, but it can vary depending on variety and growing conditions. [b] MN = most necessary, N = necessary, LsN = less necessary, LtN = least necessary.

methods recommended must be cost-effective and acceptable to farmers. Any new measures must lead to a reduction in vector-borne disease, while ensuring that rice yields can be maintained or even increased without additional costs.

It is not likely that pesticides or biological control to kill larvae in ricefields will be widely practiced soon. Public health officials do not have the funds for insecticides, equipment, and personnel to engage in such undertakings. Larvivorous fish are a possible exception. Pesticides used against rice pests sometimes kill mosquito larvae. Health and agricultural officials should collaborate to achieve mutual benefits.

There are a number of cost-effective personal protection measures that can be used to protect ricefield villages, houses, and families from mosquito vector bites. Considerable success is being achieved in several countries.

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Notes

Authors' addresses: L. S. Self, WHO Regional Office for the Western Pacific, P.O. Box. 2932, Manila, Philippines; S. K. De Datta, International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

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Malaria vectors associated with rice culture in Southeast Asia and the Western Pacific

L. T. COWPER

Malaria vectors associated with rice culture in Southeast Asia and the Western Pacific vary by country. From available data, the ricefield breeding malaria vectors are *Anopheles culicifacies, A. jeyporiensis,* and *A. sinensis,* and they are prominent in many Asian malaria transmission situations. Basic biological information on each of the three species is presented. The identification of other ricefield breeding anophelines is presented but does not encompass all reported work. Basic control methods include biological, physical, and chemical. The importance of studies on suspected or proven vectors and proposed control methods to achieve economical, technically sound, dynamic, and sustainable control in individual situations is stressed.

Malaria remains a serious threat to the orderly economic and social development of large areas of Southeast Asia and the Western Pacific despite intense national and international efforts to eradicate or control the disease over three decades. There have been enormous gains in reducing the levels of the disease during this period. The malaria control achieved in Japan; Democratic People's Republic of Korea; Republic of Korea; Taiwan, China; Malaysia; Indonesia (portions of Java and Bali); southern India; a portion of Nepal; Thailand; Philippines; Singapore; and many other areas supports the technical and administrative validity of control methods available (Cowper and Karam 1984). The rising tide of widespread insecticide resistance and parasite adaptation to the normal antimalaria drugs demands better epidemiological surveillance, operations, training, and research in present control programs. The search for alternative control methods that are both economical and practical in human terms and can be maintained over time has also intensified. Many alternatives include successful practices of the past and they can be implemented in present efforts by training and field trials. In Asia, rice is the most important food and worldwide it is reported to be the staple food of 60% of the world's population (Bang and Pant 1983). Worldwide rice production is increasing and can be expected to continue as the world's population grows. The control of disease vectors that breed in ricefields must be made more effective. The ricefield culture and practices of an area directly relate to the malaria problem because a number of mosquito vectors breed in ricefields. Malaria is associated not only with villages near ricefields but with human populations that live in the fields temporarily and seasonal laborers who move into rice-growing areas for transplanting or harvest. Seasonal laborers may not only contract the disease but transfer it to other areas. Ricefields are also breeding sites for *Culex tritaeniorhynchus* and *C. vishnui* (Philippines), the disease vectors of Japanese encephalitis as well as other diseases (Mogi 1978). This paper deals with the major identified malaria vectors associated with rice culture in Southeast Asia and the Western Pacific, with emphasis on ricefields, and to only a lesser extent on the irrigation and drainage canals. The selected references do not include publications on activities and control in riceland breeding of mosquitoes outside Asia except to illustrate comparative evidence.

Principal malaria vectors

Three species of mosquitoes are closely associated with ricefield breeding in the Asian region: *Anopheles culicifacies, A. jeyporiensis,* and *A. sinensis* (Bhatia and Krishnan 1961, Chang et al 1950, Chen et al 1967, Chow 1948, Do Van Quy and Nguyen Dang Que 1965, Furumizo 1962, Klein 1977, Pradhan et al 1979, Uchikawa 1977). However, there are many other anopheline species identified with ricefield breeding. In the hyrcanus group, *A. indiensis, A. peditaeniatus,* and *A. nigerrimus* are cited (Darsie, n.d.). Other species include *A. barbirostris, A. campestris* (proven malaria vector), *A. kochi* (postharvest), *A. aconitus* (malaria vector), *A. annularis* (malaria vector), *A. philippinensis* (malaria vector), and *A. nivipes* (Darsie 1986). Furumizo (1962) reported that in northern Thailand, 12 of the approximately 40 *Anopheles* species breed in ricefields. These included *A. kochi, A. pallidus, A. splendidus, A. tessellatus, A. vequs,* and *A. minimus.* Their importance as malaria vectors varies considerably. Some play a secondary role in malaria transmission in some locales at certain seasons and under certain ecological conditions. Continuing entomological field evaluations of *Anopheles* found in contact with humans in malarious situations are required to scientifically determine their vectorial capacity in a changing environment.

A number of malaria vectors have been identified with irrigation canals or mountain streams, which feed ricefields. In the Sallyan district of Nepal, *A. fluviatilis,* a malaria vector, breeds in irrigation canals in mountain valleys (Shreedhar Pradhan, AID/Nepal, Kathmandu, pers. comm.). In northern Afghanistan, *A. palcherrimus* and *A. maculippenis* have been studied in association with rice-growing systems and work has been done on their control by biological and other means (Artemien et al 1977).

The three important malaria vectors associated with rice culture in Southeast Asia and the Western Pacific—*A. culicifacies, A. jeyporiensis,* and *A.* sinensis—are summarized according to a compilation by Darsie (1986).

A. culicifacies Gilles

Representative sporozoite rates in the dissected salivary glands of these mosquitoes are shown in Table 1.

Table 1. Records of dissection of salivary glands of anopheline mosquitoes in unsprayed areas in three Asian countries.

Species	Country	Dissected (no.)	Sporozoite rate (%)	Ref.
A. culicifacies	India (Jabalpur District, Madhya Pradesh)	166	2.4	DeBurca (1946)
	(Delhi)	9,628	0.2	Covell & Singh (1943)
	(Orisa State)	119	0.8	Senior-White (1940)
A. jeyporiensis var. candidiensis	Vietnam	6,587	0.82	Malaria Project (1960)
A. jeyporiensis	Vietnam	5,988	0.83	Malaria Project (1960)
A. sinensis	Korea	3,093	0.06	Malaria Project (1967)

Larval habitats. A. culicifacies breeds in ricefields before and after planting, but when the rice plants are 4.7 cm tall the larvae are no longer evident. Other breeding sites include irrigation canals, riverbed pools, borrow pits, waste irrigation water, wells, and pools formed by interference with natural drainage by railways, roads, etc. Larvae can tolerate a certain amount of saline and alkaline content in their habitat water.

Seasonal prevalence. In most of its geographic range, *A. culicifacies* population peaks in September and October with a lower peak in April and May. It declines rapidly in November with low population levels from December to February. The extent and duration of irrigation correlates positively with *A. culicifacies* density.

Resting habits. A. culicifacies is predominantly a domestic species, which prefers to rest in human houses and cattle sheds during the daytime. The species will often feed in one place and rest in another. Frequently, human-blood-fed specimens are twice as numerous in cattle sheds or in combined human-cattle dwellings than in purely human habitations. In some areas it may rest outdoors in thick bushes, caves, stream banks, and culverts.

Feeding habits. The peak biting activity of *A. culicifacies* normally occurs between 2230 and 0100 h, gradually decreasing after that. Other observers report peak biting around 2400 h. This information may be important in designing community programs for malaria control.

Host selection. A. culicifacies is predominantly zoophilic. However, in a particularly epidemic year for malaria in northern India, Covell and Singh (1943) found the anthropophilic index to be 20% of the total examined. Similar samples from other areas endemic for malaria varied from 0.25 to 51.7%. In Nepal, India, and Pakistan, the anthropophilic index is normally in the 3-4% range.

Oviposition. A. culicifacies females lay their eggs while flying over the breeding habitat. They perform a hovering dance 0.75-1.5 cm above the water and drop their eggs onto the water surface. Ovipositing takes place throughout the night.

Distribution. A. culicifacies is distributed in India, Sri Lanka, Burma, Nepal, Thailand, Laos, Vietnam, Kampuchea, China, Pakistan, Bangladesh, Iran, Oman, Bahrain, Afghanistan, and Iraq, as well as in other countries.

Anopheles jeyporiensis **James**

A. jeyporiensis and *A. jeyporiensis* var. *candidiensis* Koidzumi 1924 are treated together. Studies in a hilly area in Di-linh, Vietnam, showed that the two mosquitoes occur in the same locality and are similar in their bionomics and relation to malaria transmission. Morphological differences are slight but fairly constant.

Larval habitats. The main breeding places are approximately the same as those of *A. minimus. A. jeyporiensis* is also found in seepage water, fallow ricefields, pools, ponds, and swamps.

Seasonal prevalence. The peak of *A. jeyporiensis* density in Di-linh, Vietnam, is during the southeast monsoon, July to October.

Resting habits. A. jeyporiensis is generally regarded as a “domestic” species. A great number rest in houses and cattle sheds in the daytime. In the houses, the majority prefer the lower walls. A small number were found resting under the houses and eaves, and on surrounding bushes.

Feeding habits. A. jeyporiensis is anthropophilic. The peak of biting is between 2300 and 0300 h (Do and Nguyen 1966). No data are available on the indoor and outdoor human-biting ratio, but it is assumed that this mosquito, like *A. minimus,* is endophagous.

Distribution. A. jeyporiensis is found in India, Burma, Vietnam, Laos, Kampuchea; *A. jeyporiensis* var. candidiensis is found in China (including Taiwan Province), Vietnam, Laos, Kampuchea, Thailand, Burma, India, and Nepal.

A. sinensis **Wiedemann**

Breeding habitats. A. sinensis breeds in a variety of water sources, mainly in ricefields.

Life cycle. In the insectary at constant temperature (28 °C) and relative humidity (75%), the egg stage lasts 2 d, the larval stage 10 d, and the pupal stage 2 d.

Seasonal prevalence. A. sinensis occurrence in Korea is limited to a period of 6 mo, from May to October. The first brood emerges in early May. Its density, closely related to rice cultivation, peaks in July and early August. In southern Taiwan, this mosquito is present throughout the year. Prevalence peaks twice a year in association with the two rice crops. One peak occurs in February and March and the other in September and October (Chang et al 1950).

Resting habits. A. sinensis prefers to rest in cow stables. Few remain inside houses in the daytime, but a considerable number rest at night on porches and inside before and after feeding. Daytime outdoor resting places in Korea are diverse, including potato, barley, and wheat fields; cabbage and watercress plots; rice seedbeds; and weeds alongside ditches and ponds.

Feeding habits. Generally, only a very small number of *A. sinensis* can be caught with human bait inside and outside houses (Chen et al 1967). It bites humans and animals soon after dusk and throughout the night, with a peak in the second quarter of the night.

Host selection. A. sinensis is generally known as a zoophilic species. It prefers animal blood when given free choice. In a 1965 experiment in Korea, 70 unfed *A. sinensis* were released into a hut containing a cow and 2 men; 60 fed on bovine blood, 2 on human blood. The mosquito will feed on human blood, however, in the absence of cattle (Chow 1948).

Oviposition. The female lays between 115 and 255 eggs (av 150), on the 2d to 4th nights after taking a blood meal. *A. sinensis* females can still lay their eggs in ricefields even when the plants are fully grown and densely planted, but not in water fully covered by *Azolla* and *Lemna* (Chow 1948).

Hibernation. A. sinensis adults hibernate starting at the end of October when the temperature is 13-15 °C. The most favored places are firewood and straw in storehouses close to cow stables or stacked in front of the houses. A few mosquitoes are found in culverts. In April, when temperature reaches about 19 °C, the hibernating mosquitoes resume their activities, biting cows in the open even in the daytime.

Distribution. A. sinensis is distributed in China including Taiwan, areas of Indochina, Indonesia (Sumatra), Malaysia, Singapore, Thailand, Burma, India, Bangladesh, Japan, Korea, and Hong Kong.

These descriptions will provide a basis for future control discussions and a basic template for the type of information required for each vector species under study in an area.

Principal control measures against malaria vectors

The three main operational mechanisms for the control of malaria vectors breeding in ricefields are biological, chemical, and physical (including environmental modifications and manipulations).

Biological control

There has been concerted effort over the years to use biological control, primarily fish, in developing countries, to control mosquitoes in ricefields. Larvivorous fish used for this purpose include the grass carp *Ctenopharyngodon idella* (Shumkov et al 1981), *Aphyocypris chinensis* (Yu et al 1981), *Aplocheilus latipes, Gambusia affinis, Poecilia reticulata,* and *Tilapia* spp.

Parasites are also used to control malaria vectors. They include the Mermithid nematodes, especially *Romanomermis culicivorax;* pathogens such as *Bacillus thuringiensis* var. *israelensis* (sometimes designated H-14 or Bti) and *Bacillus sphaericus* fungi such as *Culicinomyces clavisporus, Lagenidium giganteum, Tolypocladium cylindrosporum.* and, to a lesser extent, *Coelomomyces* spp. because of their complicated life cycle; viruses in the baculoviruses, microsporidia including

Nosema algerae; predator invertebrates such as water bugs and beetles; and crustaceans including microcrustaceans.

Chemical control

Larvicides or adulticides have been used to control malaria vectors for a long time. Among the larvicides available are oils, insect growth regulators, chitin synthesis inhibitors, synthetic organic compounds, monolayer films, and microbial insecticides. They are formulated as emulsifiable concentrates, wettable powders, granules, and slow-release formulations, or they may be released directly as in oil.

Adulticides can be applied as ultralow volume (ULV), sprays and fogs, or as residual sprays in a number of formulations (Ree et al 1981).

Temephos is a commonly used chemical larvicide. In Malaysian ricefields, *Culex tritaeniorhynchus* was highly susceptible to temephos. At concentrations of 60, 100, and 200 g/ha, temephos maintained ricefields free of anopheline and culicine mosquitoes for at least 2 d. When temephos was applied as a controlled-release silicate formulation at 3.83 ppm against ricefield breeders *Psorophora columbiae,* there were 80% population reductions over 71 d.

Chlorpyrifos methyl applied at 56 g/ha kept ricefields free of all mosquito larvae for at least 2 d (Yap and Ho 1977). Chlorpyrifos maintained ricefields free of *Anopheles* larvae for 2 d when applied at 14 g/ha, 3 d at 38 g/ha, and 7 d at 58 g/ha. Field application results vary from area to area. Local trials are necessary before applying any formulation to determine that it is effective, economical, and safe.

In village-scale trials in Semarang, Central Java, Indonesia, fenitrothion (ground-applied ULV) controlled human-biting *Anopheles aconitus* for 2-10 d after each application (Pradhan et al 1979). Routine ULV applications in rural areas, however, are not considered economical because of the cost and the surveillance and supervision required.

Residual spraying of structures near or associated with ricefields is a major malaria control method. Its usefulness depends on the surface composition and construction of the structures. Routine spraying of field huts or temporary laborer shelters has to be carefully assessed. For example, it may not be useful to spray villages near ricefields if the malaria patients in the village were infected in fields some distance from the village where the workers resided overnight. Each situation requires careful study to determine not only the proper control method but the insecticide or control technique to be used and the timing.

Physical control

Intermittent irrigation management, which is used widely in some districts of Japan and elsewhere, clearly depopulates larvae and influences the species composition in ricefields. Intermittent irrigation in Nagano Prefecture with the *Anopheles sinensis* group from 1972 to 1974 gave promising results. Control of vector through rotation of the spillways of small dams and the use of canals may also reduce density (Uchikawa 1977).

Conclusion

Environmental control of ricefield-breeding mosquitoes is not always practical. With the advent of the photoperiod-insensitive varieties in the mid-l960s, rice is now grown throughout the year in much of Southeast Asia, with even adjoining fields having crops at different growth stages at any time.

More effort is necessary to properly construct and maintain feeder canals and drainage ditches to reduce available breeding sites. Flushing breeding areas with fresh water is sometimes practiced where the method meets vector control requirements and intersectoral cooperation has been established. Depending on the vector, ditches can be shaded or opened to the sun.

The important consideration with any of these practices is understanding the biology of the vector and then using control methods suitable to local conditions.

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Author's address: L. T. Cowper, Communicable Disease Division, Bureau of Science and Technology, USAID, Washington, D.C. 20053, USA.

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Vector-borne diseases associated with rice cultivation and their control in Southeast Asia

Y. H. Bang

Among the vector-borne diseases associated with rice cultivation in Southeast Asia, malaria and Japanese encephalitis are of prime public health concern. With the continued expansion of water development schemes for rice cultivation, a completely new aquatic environment is created, providing more larval habitats and favorable conditions for prolonged longevity of mosquito vectors. More species of disease vectors occur in seepage-fed ricefields in hilly areas than in irrigated plains. Because authentic field data are scarce, it is impossible to accurately determine the relative importance of ricefields as larval habitats of disease vectors. In view of technical and operational limitations to chemical control of larvae in ricelands, some examples of successful bioenvironmental measures practiced before the DDT era are discussed and recommended.

In Southeast Asia, about 20% of the total agricultural land is irrigated. The irrigated area is increasing with the increased demand for agricultural production (FAI 1985). In India, for example, ricefields increased from 29.8 million ha in 1951-52 to 41 million ha in 1983-84, of which about 17.2 million ha are irrigated (FAI 1985). Of the total irrigated area, about 39.1% is irrigated by canals, 8.8% by tanks, 24.9% by tubewells, 20.7% by other wells, and 6.5% by other water sources.

Increased incidence of malaria with rice cultivation is well known (Gill 1930). Russell et a1 (1940a) showed that the entire area of Pattukkottai near Madras became malarious only after the introduction of the Cauvery-Mettur Irrigation Project in 1934 (Russell et a1 1938). In villages of Mandya District, Karnataka, the average spleen rate increased from 15.3% to 50% and deaths due to malaria increased twentyfold with the opening of the Visvesvaraya Canal (Rao 1945).

Japanese encephalitis is another important vector-borne disease endemic in the areas of rice cultivation in Southeast Asia and the Western Pacific. During the last decade, numerous outbreaks have been recorded in India, Burma, Nepal, Thailand, Malaysia, and Indonesia (Pant 1972). In India alone, between 1978 and 1987, 39, 149 cases with 14,246 deaths—a case fatality rate of 36%–were recorded (NICD 1988).

Paddy fields as larval habitat of mosquito vectors

Rice cultivation

Rice is best suited to regions of high temperatures (20-37 °C), high humidity, prolonged sunshine, and an assured water supply (Roy et al 1980). These are the very climatic conditions conducive to many sun-loving species of mosquitoes, among them many important vectors of malaria and Japanese encephalitis.

The introduction of high-yielding varieties (HYVs), while having increased production, appears to have increased the load of vector-borne diseases as well. The magnitude of the impact, however, is not fully known (Sharma 1986). Compared with indigenous varieties, HYVs are semidwarf, stiff strawed, lodging resistant, and early maturing (Roy et a1 1980). Reduction of lodging increases the amount of sunlight, which favors prolonged breeding of vectors. Early maturity of crops encourages multiple cropping, making water available in the fields for longer periods and encouraging more generations of mosquito populations. The increased use of fertilizers furthers these processes by providing rich nutrients for the growth of microflora, which are essential food for breeding mosquitoes.

Larval breeding of mosquito vectors

Many mosquito species that are disease vectors breed in ricefields (Bang and Pant 1983). Among the prime important vector species of malaria are *Anopheles culicifacies, A. annularis,* and *A. aconitus* (Pant 1972). Ricefields are also important larval habitats of all known vectors of Japanese encephalitis: *Culex tritaeniorhynchus, C. gelidus, C. fuscocephalus,* and *C. vishnui* (Reuben 1971a). In Sri Lanka, the breeding of *C. tritaeniorhynchus* in ricefields is at maximum soon after monsoon rains when the fields are covered with decaying stubble.

Mosquito larvae occur in diversified breeding places, ranging from water-filled footprints of elephants to rainwater in discarded vehicle tires. Some species are confined to a few special habitats and others breed in many different kinds of places. Not all known species of the malaria vectors in ricefields in Southeast Asia are equally distributed. The abundance and frequency of some species depend on geography (Russell and Rao 1940b), climate, and more often on stages of rice and status of ricefields (Senior White 1946).

Early investigations in India showed that 8 of 19 species collected were vectors of malaria. They were more abundant in hilly areas than in plains. They bred in seepage pools rather than in irrigated ricefields (Russell and Rao 1940b). More larvae of *A. culicifacies* were found in fallow fields than in fields of growing rice. Of those found in ricefields, density was highest in nurseries and newly transplanted fields. In contrast, *A. fluviatilis* was more abundant in fields with plants having a thicker growth than in those with a more open growth. The distribution and density of mosquito species in ricefields depends on the stage of the crop, not on the season of the year (Russell et a1 1938). The density of *A. culicifacies* was highest in saturated fields before plowing and in newly transplanted fields, but decreased steadily as the crop matured. Larval density declined with plant height. When plants reached a height of 30 cm above the water surface, larval population had dropped to almost nil.

There have been few carefully designed studies since residual insecticides were introduced. Today there are no authentic data on the relative importance of ricefields as breeding habitats of mosquito vectors (Bang and Pant 1983).

Malaria in areas with HYVs - Nainital District, India

The HYV program in India was launched in 1966-67 (Roy et al 1980). The area planted to HYVs increased from 0.9 million ha in 1966-67 to 26.6 million ha in 1985-86 (FAI 1985). In Punjab, for example, rice occupied 39.1% of the net sown area in 1984-85 kharif compared to 7.7% during 1965-66 and 13.6% during 1975-76 (Kolar and Cheema 1986). During this period, more than 20 new varieties were released in addition to those released by the state government for the specific local agroecological zones (Roy et al 1980).

Improved local varieties are better suited to wet-season cultivation. They are usually planted in June-July and mature in November-December after the monsoon season (IRRI 1975). HYVs are more commonly planted in the dry season (Kolar and Cheema 1986), and are frequently used in mixed farming with other dry season crops. HYVs are popular in the dry season because pest infestation is relatively low and the high level of solar energy allows maximum photosynthetic activity.

Before 1943, terai area of Nainital District, Uttar Pradesh, was thickly forested. It was brought under cultivation between 1943 and 1953. Terai is drained by the Sharda and Kosi Rivers and has 114 canals with a total length of 560 km. In addition, there are a large number of wells, tubewells, and artesian wells. Rice is grown in terai during the wet season, from early June to mid-October, and wheat and other upland crops are grown during the dry months (October-April). Mean annual rainfall is about 1,300 mm, 87% of which is received during the wet season. Newly transplanted fields are usually kept slightly wet for about a week until the plants are established. They are then irrigated by small field channels and water is supplied throughout the entire growing period except at tillering, heading, and flowering.

With permanent changes in the region with a network of irrigation canals, *A. culicifacies* has become the main vector of malaria in terai (ICMR 1986). In the larval collections made by the Malaria Research Centre, *A. culicfacies* was the dominant species (48%) followed by *A. subpictus* (35%) and *A. annularis* (11%). More than 95% of total *Plasmodium vivax* malaria was reported during rainy season, which coincides with peak rice cultivation activity. Ninety percent of the total *P. falciparum* malaria was from the later part of the rainy season (August-December). This malaria curve fitted with that of endemic areas.

Vectors of Japanese encephalitis in Tamil Nadu

In North Arcot District of Tamil Nadu, there are three growing seasons, but farmers grow only one or two rice crops a year, depending on water availability (IRRI 1975). The main rice season begins with the southwest monsoon (June-October) and continues until November. This is followed by a dry season crop that extends to

April. A second dry season completes the cycle. The area planted to rice varies between villages, 33-68% in the wet season and 21-61% in the dry season. In the dry season, about 90% of the total rice-growing area is planted to HYVs.

Before HYVs were introduced in 1966-67, some 10 anopheline species were known to breed in ricefields (Russell and Rao 1940a,b). *A. culicifacies,* the main vector of malaria, made up only 4.6% of the total collected in planted ricefields and 24.4% in fallow fields. Among the known vectors of Japanese encephalitis, *Culex vishnui* larvae were predominant in fallow ricefields, plowed and flooded fallow fields, or in newly transplanted fields (Reuben 1971b). *Culex pseudovishnui* and *C. tritaeniorhynchus* began to predominate when the rice grew to about 30 cm high. Larval densities did not differ significantly from the edges of fields to the interior, but more larvae were found in the area of the field farthest from water inlets.

In the presence of other breeding sources, *C. tritaeniorhynchus* breeding in ricefields was less pronounced than in wells, ponds, sugarcane fields, and irrigation channels. Likewise, in Japan, the main breeding sources of *C. tritaeniorhynchus* were ground pools, ponds, and ditches, but not ricefields (Mogi 1978). This species is not known to occur in newly planted ricefields. In established ricefields, *C. vishnui* was predominant whereas *C. pseudovishnui* was the major breeder in fallow ricefields. On the other hand, the prevalence of *C. vishnui* was related to planting time with a broad peak in the rainy season (July-October) when more than 40% of the fields were flooded. The seasonal changes in *C. vishnui* are common in transient pools without vegetation and usually scarce in water other than in fallow fields. The other two culicine species are not well understood; they are rarely caught in cattle sheds because of their daytime exophilic behavior.

The seasonal incidence of suspected cases of Japanese encephalitis also varies, but they occur throughout the year (R. Reuben, pers. comm.). At present, there are not sufficient field data to relate rice cultivation practices to the incidence of Japanese encephalitis, in at least southern India. There are few cases of Japanese encephalitis, however, in nonirrigated areas where little rice is grown. Until 1986, there had been few cases of Japanese encephalitis reported from southeastern Madras (Tanjore District) where rice is grown extensively. In the irrigated tracts of the rather dry South Arcot District, the disease is prevalent throughout the year. Similarly, Japanese encephalitis cases are reported sporadically in the Chitoor, Cuddapah, and Anantapur Districts of Andhra Pradesh. These are relatively dry districts in which irrigated rice is grown. In Karnataka, Japanese encephalitis affects Mandya District, which is extensively irrigated, and Kolar District, which is nonirrigated.

Control experiences

Control of *A. aconitus* in Indonesia

Rice culture and A. aconitus. In Central Java Province, a large-scale *A. aconitus* control program consisting of indoor residual spraying has been operating since 1952. Until 1980, more than 80% of the malaria cases in the province (75,000-150,000 cases) were reported from Banjarnegara, Wonosobo, and Purbolinggo regencies

(Bang et al 1982). Irrigated ricefields account for nearly 90% of the total cultivated land (IRRI 1975). More than 80% of the annual precipitation is received between November and April with an average monthly rainfall of 200 mm compared to about 60 mm during the dry season (May-October). There are usually two crops of rice: the wet season crop and the dry season crop, but rice at all stages of growth is usually seen at any time of the year.

Malaria occurs without seasonal interruption. A main peak usually occurs in the early months of the year (Bang et al 1982). In most of the terraced rice-growing areas, there are two seasonal peaks, the first in February-March and the second in August-September (Sustriajyu 1984). In the Banjarnegara area, the monthly slide positivity rate (SPR) fluctuated within the range of less than twofold whereas changes in the monthly rainfall were fivefold. However, geographical prevalence of malaria appears to be related to annual rainfall. There was a positive correlation between SPR and mean rainfall and between SPR and mean number of rainy days in each of the three regencies.

Although the highest larval densities of *A. aconitus* are recorded a few weeks before the harvest (March-May) of the first rice crop, the species occurs throughout the year in most areas in Java. This is probably due to the irregularity of rice transplanting since the introduction of photoperiod-insensitive varieties and improved irrigation (Sukamto 1984). Ricefields in irrigation ditches within the fields are the main breeding habitats of this *A. aconitus* (76% of total). No larvae were collected from ponds and pools within villages.

Collection of larvae from ricefields is often difficult. In the study in Central Java, it took 537 labor hours to collect 109 larvae, an average of 5 labor hours/ larva (Joshi et al 1977).

Intermittent irrigation. With financial support from the World Health Organization Tropical Disease Research Project (TDR), an intermittent irrigation trial was started in 1982-83 in a terraced ricefield area (3 km^2) in Wonosobo (Sustriajyu 1984). The ricefields were flooded for 2 d and dried for 3 d, starting when the plants were about 2 mo old. The program began by collecting preevaluation data on entomology and epidemiology, and was carried out with community education. Mosquito population was reduced 93% compared with control. Although intermittent irrigation did not reduce rice yields, its impact on overall density of *A. aconitus* and other crop pests is not yet known. The study showed the need for interdepartmental cooperation in an environmental approach to vector control (Rajagopalan 1985).

Integrated approach. Faced with the perennial problem of malaria transmission associated with the ricefield-breeding *A. aconitus* in the Banjarnegara area, Central Java provincial health authorities started an integrated vector control approach in 1985 (Sukamto 1984). The program was in collaboration with other government agencies and had the following features:

- synchronous rice planting coordinated by the Department of Agriculture;
- rotation of wet crops to dry crops, wherever possible;
- five principles to be carried out by farmers: 1. selection of prime crops, 2. proper tillage, 3. proper regulation of irrigation water, 4. proper weeding in ricefields, and 5. optimal use of pesticides against rice pests; and

- protection and conservation of forests to prevent and reduce potential larval breeding sources.

Use of larvivorous fish. The use of larvivorous fish *Peocilia reticulata* to control *A. aconitus* was a 4-yr community-action project carried out with TDR assistance in a 24-ha ricefield area (Sustriajyu 1984). Ricefields were specially prepared to maintain a slight slope so that when the fields were dried, water would drain into pits dug into the corners of every plot to ensure the survival of fish until the plots were reflooded for the rice crop when the fish could move into the floodwater.

About 20,000 *P. reticulata* were introduced initially. *Tilapia mossambica* and *Cyprinus carpio* fingerlings were also supplied to the farms so that these edible fishes, when fully grown, would be a source of food. The edible fish were given to the farmers as an incentive for them to cooperate in using *P. reticulata,* which has no food value. The data indicate that disease control can be achieved by the use of fish alone against ricefield-breeding *A. aconitus* in Central Java. The mean number of *A. aconitus* declined from 13.7 larvae/m^2 per day in 1979 to 5.0 in 1984. The SPR decreased from 16.5% in 1979 to 0.2% in 1984.

In the cultivation of fish in ricefields, the Department of Health has been responsible for seeding and monitoring fish while village chiefs guide farmers in their maintenance through agricultural village educators (Sukamto 1984). *P. reticulata* has been extensively stocked in Banjarnegara and Pagak regencies. *Aplocheilus panchax* has been distributed more extensively in the Samarang areas since 1981. However, the routine practice of rice - fish culture is yet to be documented.

Control of *A. culicifacies* in India

Intermittent irrigation. Intermittent irrigation of ricefields to control malaria in the Tanjore District of Tamil Nadu was the first such study in Southeast Asia (Russell et al 1940a). In this study, begun in 1938, dry periods not exceeding 4 d increased rice yield without detriment to quality whereas dry periods of 1 d did not control mosquito breeding. Thereafter, intermittent irrigation of ricefields was recommended as a suitable antimalaria measure in southern India, with a cycle of 5 wet and 2 dry days beginning with irrigation in mid-June to the flowering stage of rice.

During the northeast monsoon, it was not possible to drain water sufficiently to control *A. culicifacies,* but this was not considered important because this species almost disappeared from ricefields by the time the plants were 3 mo old.

The major benefits from intermittent irrigation are economical water use, higher rice yields, and control of mosquito larvae. This has been experienced widely in the alluvial plain of the Huanghe River of China (Ge et a1 1981), where the fields are flushed at 3-5 d intervals, starting 10-15 d after transplanting. This method, however, has not yet been adopted in most rice-growing areas of the region because it requires 1) a complete system of irrigation and drainage, depending on the water-holding capacity of the soil; 2) the services of highly trained irrigators; and 3) new farming techniques including soil and water management (Bang and Pant 1983).

Environmental measures. In 1941, in the Mandya irrigated area in Karnataka, a committee was formed to prevent malaria in villages. The committee, consisting of officers of the health, engineering, and revenue departments, drew up recommendations for 479 villages for a permanent solution to the malaria problem. The main recommendations of the committee were

- to create a dry belt of about 400 m around each village;
- to drain all but a few major tanks in the area;
- to build canals in valleys, which were silted and choked with vegetation, to drain seepage water and surplus irrigation water;
- to deviate channels away from dry belts wherever possible or line them with concrete; and
- to relocate populations of small, remote hamlets to larger villages, where the other protective measures had been provided.

These recommendations were implemented in 200 villages before the irrigation channels were opened. Although no other antimalaria measures were undertaken, no malaria was experienced for 5-6 yr. In addition to these environmental measures, Paris green was used in 10 demonstration villages to control malaria within the 400 m dry belt around each village. The treatment was effective for the first 4 yr, but Paris green alone was not effective in the 5th year when rice cultivation encroached on the 400 m dry belts.

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Author's address: Y. H. Bang, WHO Regional Office for Southeast Asia, New Delhi; India.

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Water management in rice cultivation and its relation to mosquito production in Japan

M. Mogi

Despite introducing regular drainage into the rice cultivation pattern, rice still needs considerable irrigation for high yields. This limits the possibilities for manipulating water to control mosquitoes. Carefully designed drainage or flushing could reduce mosquito populations under appropriate combinations of climate, soil, and human behavior. Irrigation and drainage especially designed for mosquito control may be required to increase effectiveness. Combined with the shift of transplanting time, mosquito control will be easier to achieve in temperate zones where low temperature limits mosquito breeding. Control will be more difficult in the tropics and subtropics. Required levels of mosquito control should be considered in relation to the overall integrated disease control program. Although not very effective by themselves, antimosquito measures could still contribute to overall disease control, provided they operated with other control measures and the environment is rendered unfavorable for disease transmission.

In the strict sense, water management in rice cultivation means water manipulation in ricefields in the presence of growing rice plants. In this paper, transplanting time is also referred to since it may influence the abundance of ricefield mosquitoes.

Among the approximately 20 species of mosquito larvae that occur in ricefields in Japan, the most important is *Culex tritaeniorhynchus,* a vector of Japanese encephalitis. For its larval habitat it prefers ricefields with short and sparse vegetation. The best habitat for this species is the water around seedling nurseries, and water in the ricefields after plowing and before puddling and shortly after transplanting.

The *Anopheles hyrcanus* group includes five species, some of which in the past transmitted malaria in Japan. *A. sinensis* is the most abundant mosquito species of this group in many regions. It also likes ricefields with short and sparse vegetation as a larval habitat, but the larval densities of this species in ricefields with grown rice are higher than those of *Culex tritaeniorhynchus.*

This report refers mainly to *Culex tritaeniorhynchus* on which research in Japan has been concentrated. However, it does not ignore the necessity to study species of minor importance under any given condition. Evaluation of vector potential and prediction of population trends in changing environments for each species are a prerequisite for rice field management to control vectors. Otherwise, control of the target species may be accompanied by an increase in the density of other vectors.

Fundamental aspects of water management

History

In Japan, the need for midseason drying of the ricefields to obtain higher yields was recognized early in the Edo era (at least 300 yr ago). Intermittent irrigation was suggested at the beginning of the 20th century, but it did not become a common practice among farmers until the mid-1950s. Before that ricefields were generally kept flooded as long as water was available, except for a 1-wk period for midseason drying. The 1955 rice production contest winner produced more than 10 t brown rice/ ha through the intensive application of intermittent irrigation. That prompted detailed research on the effects of intermittent irrigation and its promotion among farmers in the late 1950s. Intermittent irrigation has been common in Japan since the early 1960s.

Types of irrigation

Water management for rice cultivation includes four types of irrigation:

- stable irrigation, where the water level is kept constant by a minimum supply to compensate for the loss resulting from evaporation, transpiration, and percolation;
- renewal irrigation, where the water level is kept constant, but water is renewed periodically;
- flowing irrigation, where the water level is kept constant by continuous irrigation and drainage; and
- intermittent irrigation, where irrigation and drainage are repeated periodically.

Water management with sufficient water supply

After seedlings are transplanted in flooded fields, water is kept under stable irrigation for about 1 wk. Deep and stagnant water keeps the water temperature high and constant, and prevents seedlings from being swayed, thus facilitating root development. Renewal irrigation is practiced for the next 3 wk. The more shallow water during tillering amplifies temperature fluctuations within a 24-h period, especially when water heated by sunlight is replaced with cool water in the evening. This procedure is believed to increase the number of productive tillers. Thus, ricefields are kept flooded without interruption for about 1 mo after transplanting. Then, after a period of intermittent irrigation at 2-3 d intervals, ricefields are completely dried for about 1 wk. This midseason drying strengthens the root system, suppresses ineffective tillering, and releases harmful substances, such as hydrogen sulfate, from the soil. During the subsequent month of panicle formation, ricefields are again irrigated—stable irrigation in the northern regions or flowing irrigation in the southern regions—to protect the panicles from cold or heat damage. After heading, intermittent irrigation is continued until late-season drying in preparation for harvest. Intermittent irrigation, combined with split applications of quick-acting nitrogenous fertilizers, enables farmers to control growth and ripening to obtain high yields.

Effects of water management on mosquito production

Transplanting time

Cold-temperature zone (northern Japan). The temperature frame for rice is strict. Rice is transplanted as early as temperature permits, and harvested in late September or early October before the cold temperature. A winter crop is impossible due to low temperature and heavy snow. This environment is unfavorable for the reproduction of *Culex tritaeniorhynchus.* In May the temperature is still too low to permit extensive vector breeding. When the temperature rises, rice is already tall and dense by midseason when the fields are drained and dried. The discordance between the warm season and the stable irrigation period following transplanting keeps average population density low, and the vector population peaks unpredictably between June and September when weather factors and rice cultivation practices, by chance, combine to favor ricefield-breeding mosquitoes.

Warm-temperature zone (southern Japan). In southern Japan, the temperature frame for rice cultivation is longer and a winter crop (other than rice) is possible. Transplanting time is variable (late March to mid-September), even between neighboring localities with a common climate, according to the requirements of the winter crop, of summer labor for other than rice cultivation, and of early harvest before the typhoon season. In Nagasaki Prefecture, rice cultivation still follows the traditional calendar and transplanting takes place during the rainy season, which precedes the hottest season. In this region *Culex tritaeniorhynchus* populations start to increase in density immediately after transplanting and reach their annual adult density peak in late July or early August. Population densities begin to decline as the rice crop grows and the intermittent irrigation gives way to midseason drainage. In Mie Prefecture, transplanting shifts to May when temperature is still high enough to permit growth of the vector population. Therefore, the first peak of adult populations shifts to June, and it may be higher than later peaks (Maruyama 1971). No data are available concerning the effect of earlier transplanting in April or late March, but it can be inferred that the growth of the vector population is significantly suppressed because early-season temperatures are too low for the vector population to propagate and later, when temperature is optimum, the ricefield environment has turned unfavorable. The situation could be compared with that in northern Japan.

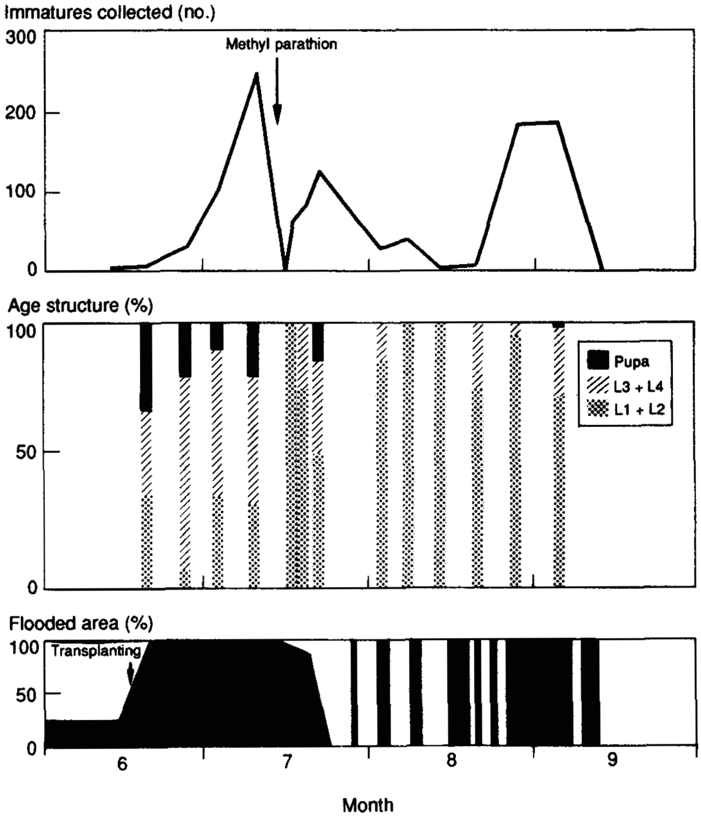
Subtropical zone (Ryukyu Islands). In the Ryukyus, double cropping of rice is possible. Typically, transplanting is done around March and August, and the peak in vector density follows the midsummer transplanting, but mosquito vector species can even breed during midwinter. In this region, a shift in transplanting time offers little possibilities to control ricefield mosquitoes.

Implications for mosquito control. The change of transplanting time in temperate regions offers the possibility to level out peak densities of mosquito vectors that have a preference for ricefields with short and sparse vegetation, particularly if it is combined with subsequent intermittent irrigation and midseason drainage.

Intermittent irrigation and drainage

Potential and evidence. Theoretically, drainage is the best approach to control ricefield-breeding mosquitoes. Intermittent irrigation can also be effective if the irrigation periods are shorter than the larval and pupal stages of the mosquitoes. The minimum period for hatched larvae to develop into adults in ricefields is about 1 wk for *Culex tritaeniorhynchus* and a little longer for *A. sinensis* in the hottest season. Therefore, irrigation periods shorter than 1 wk prevent the production of adults even though larvae hatch.

In fact, a considerable number of *Culex tritaeniorhynchus* immatures were collected from ricefields even in short irrigation periods of 1, 2, 2, 4, 1, and 1 d, but the population consisted mostly of 1st- and 2d-instar larvae; pupae were found only in stable irrigation periods after transplanting (55 d) and during panicle formation (12 d) (Figure 1).

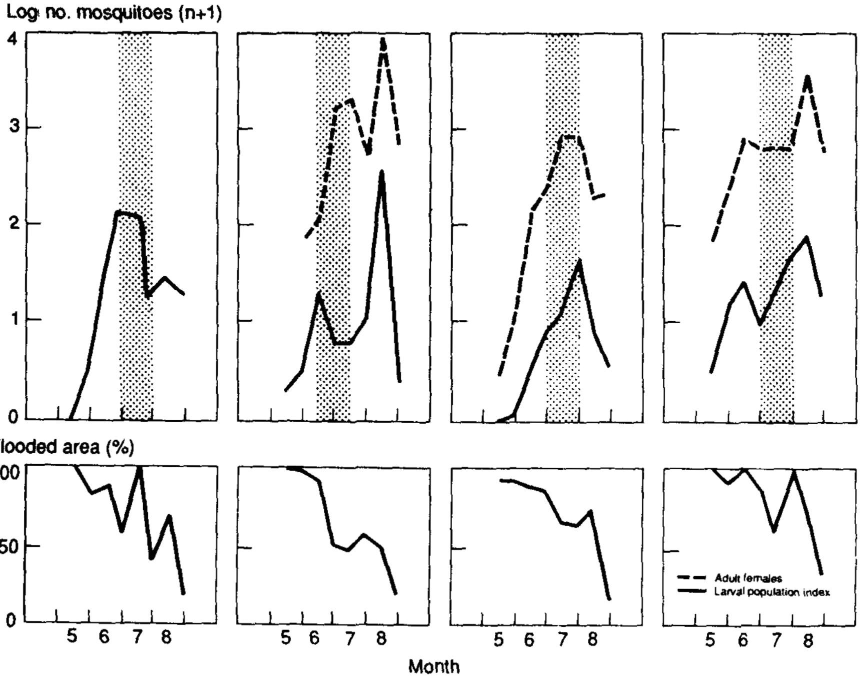


1. Effects of rice cultivation practices on immature populations of *Culex tritaeniorhynchus* (after Ogata and Nakayama 1963). Five dips were taken from each of 5 ricefields and 1 ditch. L1 = 1st instar, L2 = 2d instar, L3 = 3d instar, L4 = 4th instar.

More extensive studies on *Culex tritaeniorhynchus* were carried out in two ricefield areas of Mie Prefecture, where intermittent irrigation is commonly practiced. In 3 of 4 study years, population density indices of larvae and/or adult females decreased during intermittent irrigation (with flooding and drainage periods each of about 1 wk duration), then increased following stable irrigation. In the third year, when drainage was less complete than in the other study years, larval and adult populations increased exponentially during the intermittent irrigation period (Fig. 2).

Facts from other regions. In Okayama Prefecture, adult mosquitoes have been continuously collected for more than 50 yr (the longest period directed by Prof. Inatomi) since the pioneer work on the epidemiology of Japanese encephalitis in 1933. Although collection methods and sites varied, this is the longest record of mosquito collection in Japan. Analyses for *Culex tritaeniorhynchus* and *A. sinensis* indicate that yearly population peaked most frequently in late July and early August, both before and after 1960, but that after 1960 peaks were concentrated more in late July. That shift in peak populations means that the probability of population growth in the period after initial stable irrigation has been reduced. Among other things, the widespread use of intermittent irrigation may be largely responsible for this change inasmuch as transplanting time has remained unchanged in the survey area.

However, it should not be overlooked that there is no evidence of a reduction in peak density in late July and and early August following the adoption of intermittent



2. Effects of intermittent irrigation on *Culex tritaeniorhynchus* populations (after Sugiyama 1986). Population density indices were calculated from 1) number of adult females attracted to dry ice, and 2) no. of larvae/ m^2 × % flooded area. Vertical lines represent period of intermittent irrigation.

irrigation. This is inevitable, because the optimal breeding habitat, i.e., ricefields for about 1 mo after transplanting, remains.

Many studies show the difficulty of reducing the biting population of *Culex tritaeniorhynchus* by intermittent irrigation and midseason drainage. For example, in Toyama Prefecture (5 localities for 3 yr) (Kamimura and Katori 1969) and in the Miyagi Prefecture (1 locality for 7 yr) (Ishida et al 1976), the number of adult females attracted by pigs (the amplifier reservoir host for the Japanese encephalitis virus) fluctuates without any predictable trend attributable to intermittent irrigation and midseason drainage. This is due to

- the variability in dates on which drainage begins and ends in individual ricefields,
- incomplete drainage caused by land characteristics such as soil permeability, groundwater level, and depressions in fields,
- incomplete or no drainage by farmers who are occupied mainly with other jobs, and
- rainfall offsetting the effect of drainage.

Adult migration from neighboring areas may also be involved.

Implications for mosquito control. Intermittent irrigation has the potential for combining higher rice yields with mosquito control by systematic drainage. Its effectiveness is limited, however, because rice still needs a considerable duration of irrigation for high yields, and intermittent irrigation is subject to various artificial and natural factors. Mosquito control by intermittent irrigation and drainage can be effective only when it is practiced

- simultaneously for all ricefields over a large area,
- during the entire cropping season, and
- under land and weather conditions that favor rapid drying.

A problem accompanying drainage is the adverse effect it may have on nontarget organisms, including aquatic predators, of which about 30 species are confirmed to kill mosquito larvae in the laboratory (Sugiyama et al 1985, Watanabe et al 1968). The most important species are of the family of Odonata (dragonfly and damselfly, nymphs), Notonectidae (backswimmer, nymphs and adults), Dytiscidae (predacious water beetle, adults and larvae), and three species of fish, *Orizias latipes, Carassius gibelie* and *Misgurmus fossilis.*

Impacts of predation in the field were measured by comparing the natural survival of *Culex tritaeniorhynchus* with that in predator-free cages (Mogi et al 1980), and estimating the number of *A. sinensis* larvae killed by Odonata nymphs *(Sympetrum frequens)* using the precipitin test (Urabe et al 1986). Both studies showed that predation is the most important source of larval mortality.

The effects of drainage on aquatic predators have not been studied.

Predators capable of flying away from drained ricefields (adults of Dytiscidae and Notonectidae) may move to other aquatic habitats and recolonize the fields after irrigation. Even these predators, however, may be adversely affected by drainage if the reproductive period is seasonal and flightless immatures die when the ricefields are drained. Populations of aquatic predators such as fish, which cannot survive a dry period by emigration or quiescence in the soil would diminish significantly and would require more time to recover unless the irrigation water source contains enough stock for recolonization of the ricefield. Therefore, better mosquito control by complete drainage of a large area could render irrigated ricefields more favorable habitats for mosquito breeding when they were reflooded, particularly if other conditions remained unchanged. This problem is not very serious in temperate Japan since late-season mosquito reproduction is limited by falling temperatures and photoperiod-induced diapause. In tropical regions, where temperature is suitable for mosquito reproduction all year around, this aspect of drainage assumes more importance.

Flowing irrigation and flushing

Terraced ricefields. Flowing irrigation is common in terraced ricefields along valleys. Generally, each ricefield is small and has single inlets and outlets for irrigation and drainage. Irrigation is introduced into the uppermost ricefields and flows to successively lower ricefields before being discharged into rivers or canals at the lowest point. Because individual ricefields are small, the hypothetical renewal time (calculated simply as a quotient of water volume in each ricefield and the inflow, which is nearly equal to outflow) frequently is several hours or less. In reality, water flows only along a narrow area between the inlet and the outlet while surface water remains stagnant for the most part (Mogi 1979). Gravid females of *Culex tritaeniorhynchus* lay eggs exclusively on the surface of stagnant water and the larvae have little chance of being taken up by the current. As a result, pupae may be abundant in the uppermost ricefield of the system, if the conditions there are attractive to gravid females. Although some larvae may be carried further down the system, this does not imply the loss of larvae from the area but a change of distribution except for larvae discharged directly into the rivers or canals from the lowest ricefields. Therefore, under normally flowing irrigation water currents do not significantly affect mosquito populations. On the contrary, water currents may to some degree favor the reproduction of mosquitoes that prefer slowly running water for their larval habitat.

When water levels rise during heavy rain, water overflows the levee at various points. This multisluice situation induces water currents over the entire surface, resulting in a drastic loss of mosquito immatures from the terraced ricefields. Terraced ricefields are common in Nagasaki Prefecture and the rivers collecting water from the irrigated areas have to flow only a short distance before discharging into the sea. Summer precipitation in this region is inversely correlated with the incidence of Japanese encephalitis, which explains the annual fluctuation of about 50% in the extent of the epidemic (Mogi 1983). This strong correlation between precipitation and disease incidence is best explained by the catastrophic loss of *Culex tritaeniorhynchus* immatures to heavy rains.

Flatland ricefields. In Saga Prefecture next to Nagasaki, ricefields are developed mainly on alluvial plains or on reclaimed flatland and are generally large. In this region, important epidemics of Japanese encephalitis still tend to occur in dry summers but this tendency has not been confirmed statistically. In Saga, heavy rains are less catastrophic for the vector population than in Nagasaki, and other factors are relatively more important.

Implications for mosquito control. Artificial flushing could be effective in terraced ricefields if in each ricefield multiple sluices were arranged to induce water currents over the entire surface. Flushing for the control of ricefield mosquitoes requires excess irrigation water and irrigation facilities that carry the flush water to places unfavorable for the survival of mosquito immatures or concentrates them in small areas where they can be treated by chemical or biological means. Without meeting the last demand, flushing might cause outbreaks of mosquitoes downstream. After continuous heavy rains which washed out ricefields along the valley, an increase in *Culex tritaeniorhynchus* and *A. sinensis* populations has been reported from villages nearby the reservoir dam where a vast amount of larvae accumulated (Sakakibara 1965).

The impact, if any, of flushing on aquatic predators of mosquito larvae may be less severe than that of intermittent irrigation or midseason drainage. Adults of a very small species of Dytiscidae (2 mm) have been observed in water flowing out of ricefields along with *Culex tritaeniorhynchus* and *A. sinensis* (Sugiyama 1986). Predators living on or in mud (dragonfly nymphs), those clinging to submerged vegetation (damselfly nymphs), and those with strong swimming ability could resist water currents strong enough to wash away mosquito larvae. This may be an advantage of flushing over drainage in terraced ricefields that contain a complex of predator species important in the natural control of mosquitoes.

Conclusion

Despite the introduction of regular drainage into its cultivation pattern, rice still needs a considerable period of irrigation for high yields. This limits the possibilities for water manipulation to control mosquitoes. Carefully designed drainage and flushing could reduce mosquito populations under appropriate combinations of the right climate, soil, and human behavior. Irrigation and drainage schemes especially designed for mosquito control may be required to increase effectiveness. Combined with the shift of transplanting time, success will be easier to achieve in temperate zones where the period favoring mosquito reproduction is shorter. In subtropical and tropical regions, successful control will be more difficult to achieve.

Mosquito control is aimed at reducing or eradicating mosquito-borne diseases. Required levels of mosquito control should be considered in relation to the whole scheme of disease control. Although not very effective by themselves, antimosquito measures could still make an important contribution to an overall disease control strategy in combination with other disease control measures by rendering the environment unfavorable to disease transmission. In Japan, ricefields still produce vast numbers of *A. sinensis* and *Culex tritaeniorhynchus,* but endemic malaria has disappeared and Japanese encephalitis incidence has been greatly reduced. This situation, which may be referred to as *anophelism without malaria* and *culexism without Japanese encephalitis,* is a more practical goal than complete eradication of vectors. Water management to control ricefield mosquitoes, by itself far from effective, could be an important component in an integrated disease control program.

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Author's address: M. Mogi, Saga Medical School, Nabeshima, Saga 840.01, Japan.

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Environmental management for the control of ricefield-breeding mosquitoes in China

Lu Baolin

Two mosquito species, *Anopheles sinensis* (vector of malaria) and Culex *tritaeniorhynchus* (vector of Japanese encephalitis) are notorious ricefield breeders in China. Environmental management is one of the most important components of the vector control strategy. For these two species population densities follow rice cropping patterns and peak at certain stages of rice production. Therefore environmental management approaches for their control focus on agricultural practices and water management in ricefields. Manipulation of seedling beds has reduced mosquito propagation early in the season. However, a more effective vector-control measure has been intermittent irrigation and several regimes have been tested. The most successful and economical of these, the wet-irrigation method, is described in detail. It is extensively applied in Henan Province. In addition, it is attractive for the farmer because it gives higher yields. Currently under investigation is the effect of *Azolla* on the ecology of mosquito vectors breeding in ricefields. Because of its N_2-fixing ability, *Azolla* is widely used as an organic fertilizer. Preliminary laboratory experiments indicate that *Azolla,* when it covers the entire water surface of ricefields, interferes with the oviposition and aquatic stages of mosquito vectors.

In many parts of the world, vast areas of irrigated ricefields offer favorable breeding places for many species of mosquitoes, including some important vectors of malaria, Japanese encephalitis, and other vector-borne diseases. The control of these riceland-breeding mosquito vectors is therefore an important public health issue in many countries. The People's Republic of China, which has the largest area of irrigated ricefields in the world, has given much attention to this problem.

Irrigated ricefields are the main breeding places of *Anopheles sinensis* Wiedemann and *Culex tritaeniorhynchus* Giles, which are the most widely distributed species in China. The former is an important vector of malaria and of Brugian filariasis in the flatlands, and the sole vector north of 34°N (Lu 1982, Zhou 1981). It has been the incriminated vector in more than 70% of the malaria cases reported in recent years. *C. tritaeniorhynchus* is the main vector of Japanese encephalitis.

Owing to the exophilic or semiexophilic habits of adult mosquitoes of both species, attempts to control transmission by spraying indoor walls with residual insecticides have been unsatisfactory. Various chemical larvicides such as HCH and temephos are effective in the laboratory, but field application is impractical because of the inaccessibility of the breeding places, setbacks caused by insecticide resistance, and environmental considerations. Different formulations of *Bacillus thuringiensis* serotype H-14, which are highly toxic to *C. tritueniorhynchus,* posed difficulties in application similar to those encountered when chemical larvicides were field-tested. Therefore, alternative control methods should be sought.

To better understand the problem, national cooperative studies on the integrated management of ricefield breeding mosquitoes were begun in China in 1978, sponsored by the Office of the Central Committee of Patriotic Health Campaign. Environmental management was considered one of the important control approaches. In this paper the main results obtained are introduced together with the outcome of some recent studies in China.

Effect of rice cultivation on the mosquito population

No less than 40 species of mosquitoes breed in varying densities in ricefields in China. Except in a few localities such as parts of Ningxia Province, where the larvae of *C. modestus* Ficalbi are the most common species, *A. sinensis* and *C. tritaeniorhynchus* are the predominant ricefield breeders (Table 1) throughout their distribution range.

Although these mosquitoes may breed in other types of water bodies including swamps, ponds, ditches, grassy pools, etc., the ricefields remain their most important breeding habitat. Hence, their usual abundance in the rice-growing rural areas in the plains, where they generally account for 50-70% or more of the mosquitoes feeding on domestic animals and on humans.

The effects of rice cultivation on the population dynamics of these two vector species has been further demonstrated by their seasonal distribution. It is well documented that, in many parts of China, their seasonal distribution is influenced not only by atmospheric temperature and rainfall but also by the accumulation of water in the ricefields. For instance, in Henan Province, the mosquito larvae begin to appear within 10 d after transplanting (Fig. 1) with density increasing steadily to a peak during the crop heading stage in August. Larval densities decline rapidly after the ripening stage as the fields are drained before the harvest in October.

Moreover, seasonal variations of adult populations of both species normally coincide with the number of rice crops per year, i.e., one peak in single-cropped areas and two peaks in double-cropped areas. For example, in single-cropped areas north of the Yangtze River, *C. tritueniorhynchus* shows a single peak in adult density around August (Zheng et al 1980) (Fig. 2), whereas in double-cropped areas in the vicinity of Shanghai, usually two peaks are observed, one in late June and the second in August (Fig. 3).

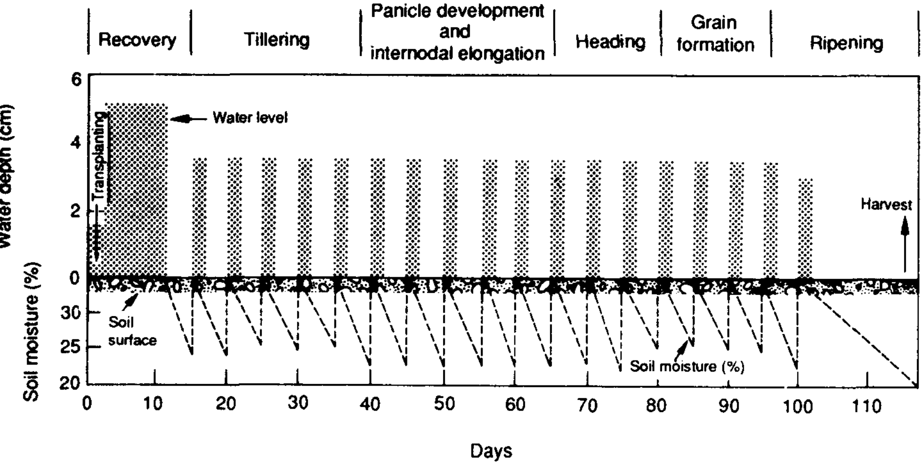
Similar seasonal distribution patterns of adult *A. sinensis* have been observed.

A number of observations show the relation between rice cultivation and population densities of *A. sinensis.* For example, in Luyi county, Henan Province, 1971 to 1982 data show that the adult mosquito density is proportional to the area of

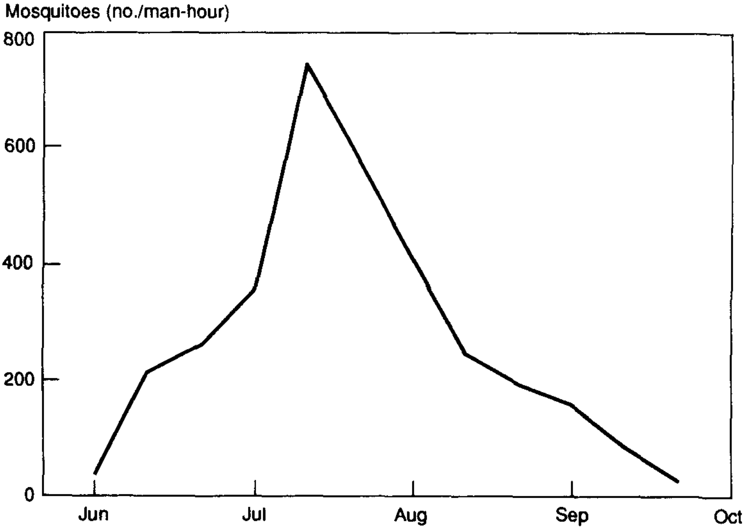
Table 1. Larval composition in ricefields in China.

Locality	Total larvae collected (no.)	Number of larvae of different species collected and percentage of total					
		A. sinensis		*C. tritaeniorynchus*		Others	
		No.	%	No.	%	No.	%
Quanzhou, Guangxi (Jun 1983)	480	105	21.9	375	78.1		
Tongbai, Henan (Jul-Aug 1984)	1381	960	69.5	99	7.2	322	23.3
Cili, Hunan (Jul-Aug 1984)	8266	2,848	34.5	5,317	64.4	101	1.2
Danyang, Jiangsu (Jul-Aug 1985)	1995	994	49.8	1,001	50.2		
Wanza, Jiangxi (Jul-Aug 1985)	481	413	85.9	68	14.1		
Shenyang, Liaoning (Jul-Aug 1984)	361	228	63.2	116	32.1		
Yongning, Ningxia (Aug-Sep 1973)	1524	8	0.5	6	0.39	1,510[a]	99.1
Zhongwei, Ningxia (Aug-Sep 1982)	3702	885	23.9	1,564	42.2	1,013	27.4
Yuci, Shangxi (Jul-Aug 1984)	212	50	23.6	76	35.8	96	45.3
Chengdu, Sichuan (Jul-Aug 1985)	975	485	49.7	490	50.3		

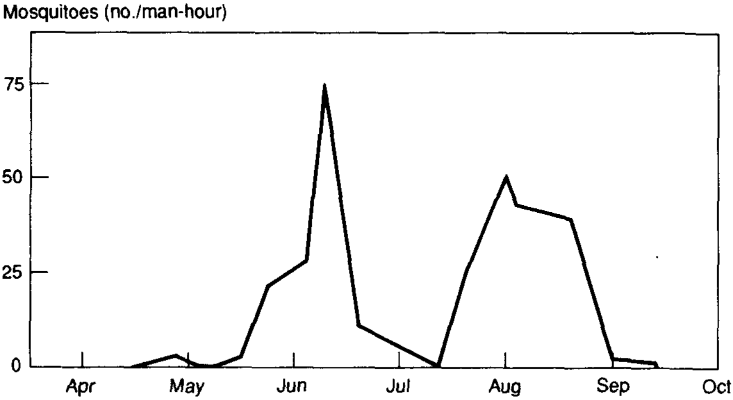
[a] 82.3% of the larvae were *Culex modestus,* ferocious biter



1. Diagram of wet-irrigation method from transplanting (day 0) to harvest in rice cultivation in Henan Province. China (modified from Ge et al 1981).



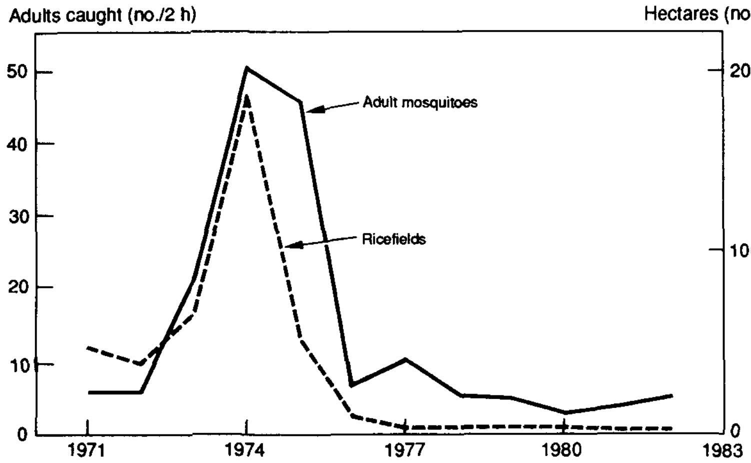
2. Seasonal distribution of *C. tritaeniorhynchus* in a rice single-cropping area, Beijing, China (after Zheng et al 1980).



3. Seasonal distribution of *C. tritaeniorhynchus* in a rice double-cropping area, Shanghai, China (Lu 1984).

irrigated ricefields (Antimalaria Research Station of Henan Province 1983, unpubl.) The mosquito density peaked in 1974, when the total rice area was highest, and declined sharply as the ricefield area was greatly reduced by a shift to other crops (Fig. 4).

Because *A. sinensis* is the sole vector of malaria in these parts of China, morbidity due to malaria is positively correlated to adult density and in turn to the area planted to rice (Lu 1983, unpubl.).



4. Relation between density of *A. sinensis* and ricefield area in Quangtang District, Luyi county, Henan Province, China (after Antimalaria Research Station, Henan Province 1983).

These two examples clearly demonstrate the importance of ricefields as breeding places for mosquitoes. Control of ricefield breeding is crucial. Improvement of rice planting methods and of irrigation management are key issues in any attempt to render ricefields less suitable habitats for mosquito breeding. This refers in particular to the correct manipulation of seedling beds and methods of ricefield irrigation.

In the past, seedling beds were the main habitats of the first-generation larvae of *A. sinensis.* They have traditionally been the first target areas for the application of larvicides in the conventional approach to vector control. In recent years, however, few or even no larvae can be found in seedling beds in many parts of China. This important change is due better seedling bed management (Lu 1979).

Currently seedlings are cultivated in beds 1.5 m wide separated by interditches about 25 cm wide and 10 cm deep. Separate channels carry irrigation and drainage water. The beds are kept wet for 3-5 d after sowing to promote rooting of the seedlings. From seed germination to the two-leaf stage of the seedlings, the beds are irrigated and drained according to prevailing weather. Generally, during the period before the grain-rain, which normally occurs between seeding and transplanting (April 20), the beds are irrigated in the evening and drained in the morning. After the grain-rain, the schedule is reversed, i.e., they are irrigated around 0900 hand drained in the evening. Fertilizers must be applied promptly at the three-leaf stage, and the beds should be irrigated shallowly and more frequently. When the seedlings have developed 4 or 5 leaves, the beds are drained. Proper irrigation and drainage at this stage not only may increase the survival rates of the seedlings by preventing their decumbence and rotting, but also could prevent or reduce the breeding of first-generation of *A. sinensis,* and, in some parts of China, of *C. tritaeniorhynchus.*

Wet-irrigation method for the control of mosquito larvae in ricefields

In recent years a number of alternative vector control measures have been tested in China, among them various types of intermittent irrigation. A method known as wet irrigation was the most successful (Lu 1984).

The wet-irrigation method

Immediately after transplanting the ricefields are kept flooded until the seedlings have recovered. The water is then drained and the wet-irrigation method begins. Water is supplied according to the needs of plants. Fields are intermittently flooded to a shallow depth. The floodwater may disappear within 24-48 h through absorption, percolation, and evaporation. Typically, an irrigation interval of 5 d gives the highest rice yields. An indication of soil moisture at the end of the drying period is that it may be stepped in without leaving deep footprints. The field duration of the rice plants is about 100 d; during this period the fields are irrigated about 20 times. Irrigation interval, water depth, soil moisture, and growth stages of the crop are shown in Figure 1.

The most favorable period for larval breeding is during recovery of the transplanted seedlings, which lasts 10-15 d with a water depth of 4-6 cm. An improved transplanting method has been recently introduced in many regions, which shortens the recovery period and reduces the time of mosquito breeding. In conventional irrigation the fields are flooded throughout the growing period except for the late ripening, tillering, heading, and stages, when, in some regions, the fields are drained for 4-10 d.

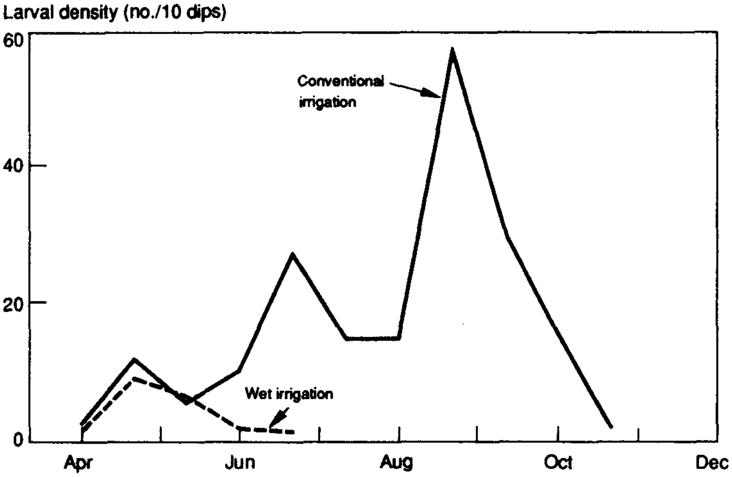
Effect on survival of immature stages and larval density of mosquito vectors

The eggs of *A. sinensis* can survive a considerable time on the soil surface of a drained ricefield. For example, at a surface temperature of 25 °C and soil moisture of 20-30%, 50% of the eggs will still hatch after 5 d. The eggs of *C. tritaeniorhynchus* are more vulnerable and at similar temperature and soil moisture will not hatch within the same period.

The larvae and pupae of both species survive for a much shorter time after fields are drained. All larvae of *A. sinensis* die within 3-4 d and no pupae survive after 4-5 d (Ge et al 1981).

Although the immature stages of both species can survive for a few days on the soil surface during intermittent dry periods, repeated draining of the field, of course, interferes with the oviposition by females, as well as with the growth and survival rates of larvae and pupae. Larval densities in wet-irrigated fields are much lower than those in conventionally irrigated fields (Fig. 5). In wet-irrigated fields larval density decreases rapidly after the recovery stage of the seedlings.

Where wet irrigation is practiced, the adult populations are notably reduced as a result of the lower larval density. Compared with the control areas in Henan Province, the adult density of *A. sinensis* was reduced by 53-55% and that of *C. tritaeniorhynchus* by 55-70%.



5. Comparison of larval densities of *A. sinensis* and *C. tritaeniorhynchus* in wet-irrigated and conventionally irrigated fields (modified from Ge et al 1981).

Cost-effectiveness

Proper application of wet irrigation leads to better developed root systems of the rice plants and prevents decumbence, increasing average rice yields by about 10%. In some parts of Henan Province, the average yield of wet-irrigated fields amounted to 7.2 t/ha, whereas yields in conventionally irrigated fields averaged 6.3 t/ha, a 13% difference.

Also, water consumption of wet-irrigated rice cultivation is much lower than that in conventional irrigation. Based on small-plot experiments, water consumption under wet irrigation was calculated at 9,000-10,500 m^3/ha, while 22,500-27,000 m^3/ha was needed for an entire rice crop cycle with conventional irrigation.

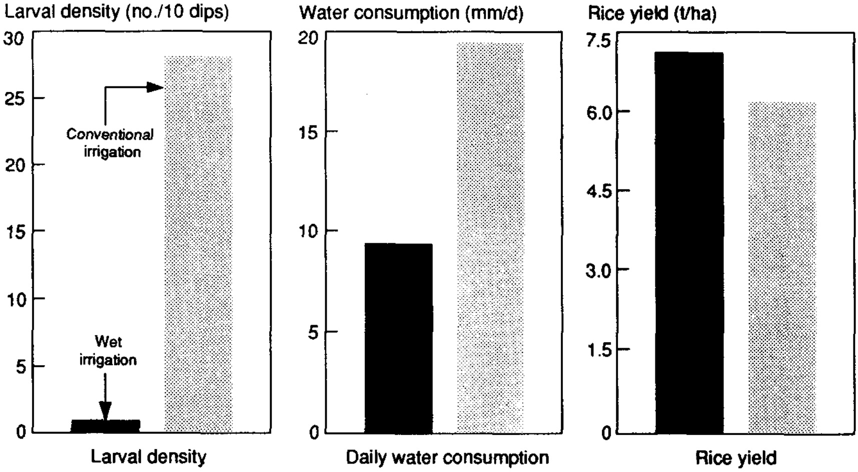
A comparison of larval density, crop yields, and water consumption under conventional and wet irrigation is shown in Figure 6.

Although it is difficult to compare the costs of the 2 irrigation systems directly, the 13% yield increase and 50% reduction in water consumption of the wet-irrigation method, with the attendant reduction in labor and electricity use, give this system clear cost advantages.

The wet-irrigation method has been welcomed by farmers, and it is expanding to more farms. More than 35,000 ha of ricefields in Xinxiang region alone are now using wet irrigation.

Wet-irrigation practice in Henan Province

The wet-irrigation method was originally studied, developed, and promoted in the alluvial plains of the Yellow River basin by our collaborating unit, the Henan Provincial Hygiene and Anti-epidemic Station, in cooperation with the Institute of Field Irrigation of the Bureau of Water Resources Conservancy and the Xinxiang Institute of Agricultural Research of Henan Province.



6. Comparison of larval density, crop yields, and water consumption in wet-irrigated and conventionally irrigated ricefields (after Ge et al 1981).

Wet irrigation in Jiangsu Province

It was thought that wet irrigation could be used successfully only in the alluvial plain of the Yellow River basin (Lu 1981, unpubl.), but recent studies showed it can be similarly successful in some parts of Hebei and Jiangsu Provinces.

In Ganyu county of Jiangsu Province, intermittent irrigation has been followed locally since 1979. The fields are irrigated after complete drying and then flood is maintained 3-7 d. In 1982 the wet-irrigation method was tried on 3.7 ha. The method was nearly the same as that used in Henan Province, except that the intermittent drying periods were less than 5 d. Results were similar to those obtained in Henan Province.

The effect of azolla on mosquito breeding

Azolla is a free-floating, aquatic fern that lives in symbiotic association with a species of blue alga, *Anabaena azolla,* which fixes atmospheric nitrogen in sufficient quantities to ensure rapid growth of the plant. The *Azolla-Anabaena* complex is a source of organic fertilizer and may be considered aquatic green manure. It is of particular interest in rice cultivation and has been utilized to various extents in China and many other countries to improve soil fertility.

Azolla grows rapidly and under favorable conditions can cover a given water surface completely within 10 d. The potential detrimental effect of water surface coverage by azolla on mosquito breeding was suggested in China as early as 1934 by Li and Wu (1934), but so far the hypothesis has not been systematically studied. In 1986, our institute initiated a study on the effect of azolla on mosquito breeding with support from the World Health Organization. Preliminary results were published in the PEEM Newsletter (PEEM 1986).

Table 2. Effect of azolla coverage on the Oviposition of culicine mosquitoes in cage studies.

Species	Tests (no.)	Egg rafts (no.) collected in different oviposition containers		
		Complete azolla coverage	2/3 azolla coverage	Control
C. modestus	8	0	108	375
C. pipiens pallens	2	0	7	86
C. quinquefasciatus	3	0	1	130
C. tritaeniorhynchus	7	0	47	180

Table 3. Effect of azolla coverage on development of 4th-instar larvae and subsequent emergence of pupae of *Anopheles sinensis* in age studies.

Experiment	Larvae observed (no.)	Adults (no.) that emerged in different containers		
		Complete azolla coverage	2/3 azolla coverage	Control
1	100	0	82	95
2	100	0	94	93
3	100	1	83	85
4	100	3	78	82
Total	400	4	337	335

In 1986 laboratory studies of the effect of azolla on mosquito breeding were done in cages under controlled conditions. They showed that complete coverage of the water surface by azolla definitely inhibits oviposition of *Culex modestus, C. pipiens pallens, C. quinquefasciatus,* and *C. tritaeniorhynchus* (Table 2). Similar cage studies on *A. sinensis* showed that although the total number of eggs collected in seven containers with complete azolla coverage was less than the number of eggs collected from partly covered and uncovered control containers, the difference was not statistically significant.

Because azolla coverage did not prevent oviposition by *A. sinensis* females in the breeding containers, the effect of azolla on the development of 4th-instar larvae and the emergence of pupae was studied in containers with complete azolla coverage or two-thirds coverage. Complete coverage by azolla is definitely detrimental to adult emergence (Table 3,4).

Conclusion

In China, ricefields are the main breeding places of two important disease vectors, *A. sinensis* and *C. tritaeniorhynchus.* Effective control of these vectors continues to

Table 4. Effect of azolla coverage on emergence of pupae of *Anopheles sinensis* in cage studies.

Experiment	Pupae observed (no.)	Adult emergence in different containers					
		Complete azolla coverage		2/3 azolla coverage		Control	
		No.	%	No.	%	No.	%
1	60	23	38.3	59	98.3	59	98.3
2	55	16	29.1	52	94.5	54	98.2
3	90	34	37.8	84	93.3	90	100.0
4	90	24	26.7	90	100.0	90	100.0

pose problems. Because of the vast extension of ricefields, and the complexity of ecological conditions in different parts of the country, an integrated vector control strategy offers the greatest chance of success, if implemented at the village level with active participation by farmers. The wet-irrigation method is a suitable way to tackle the problem. Its advantages of reducing larval densities and water consumption, as well as increasing crop yield, favor its promotion. A further expansion of the use of wet irrigation can be expected in China.

Nevertheless, this method can be adopted only in a limited part of the 100 million ha of ricefields. However, observations made in Shanghai, Jiangsu Province, and other regions show that different types of intermittent irrigation can be adapted to local conditions, which may also reduce larval densities. It is particularly encouraging that the promotion of upland rice cultivation has been initiated in parts of Henan and Hebei Provinces, where mosquito breeding does not occur. Indications are that the control of ricefield mosquito vector breeding might be solved ultimately only through innovative planting and irrigation.

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Author's address: Lu Baolin, Department of Vector Biology and Control, Institute of Microbiology and Epidemiology, P.O. Box 130, Beijing 100850. People's Republic of China

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Malaria and rice: strategies for control

J. A. Najera

Various approaches to malaria control in riceland ecosystems and the factors that determine their success or failure are reviewed. The malaria epidemiological patterns of rice-growing areas varies greatly throughout the world. Rice cultivation has been associated with increased malaria transmission in many areas, while in other areas rice cultivation favors nonvector anophelines and is associated with reduced malaria transmission. The interplay of factors related to mosquito genetics, social, and ecological changes affecting man-vector contact, and specific control interventions is analyzed. The current WHO strategy for malaria control based in the primary health care approach is presented. This strategy aims at providing the whole population with appropriate diagnosis and treatment of disease and health education to promote personal and community protection against transmission. This strategy should be complemented by referral systems and the development of epidemiological services, which should organize transmission control interventions in problem areas. The identification of problem areas and the planning and execution of appropriate interventions should follow a research and development approach. The approach should maximize 1) the application of existing knowledge, 2) the opportunities for learning by experience, and 3) the documentation and dissemination of acquired knowledge.

Malaria has been one of the main environmental determinants of human settlement since Neolithic times. The intensity of the malaria risk was an important factor to identify an area as healthy or unhealthy and, whenever people had a choice, permanent settlements in malarious areas were avoided.

Agricultural practices were recognized early as modifiers of the malaria risk of an area. Popular wisdom synthesized such observations in sayings such as “malaria flees before the plow.” The recognition of the dangers of swamps and the benefits of their drainage or other forms of sanitation were an established art at the time of Roman expansion. Empedocles of Agrigentum, pupil of Pythagoras, living in Sicily in the fifth century B.C., is said to have saved the city of Selinus from disease by changing the courses of two neighboring rivers.

Rice cultivation, with its water requirements, has also given rise to important epidemiological observations, which occasionally were translated into regulations of its culture. In China, as early as 2800 B.C., ceremonial ordinances for rice planting were established by imperial decree.

Rice cultivation was introduced into Europe by the Arabs in the Middle Ages. Christians often resisted rice cultivation in the name of public health. About a century after the Aragonese conquered the Arab Kingdom of Valencia, rice cultivation was considered a public health menace and was forbidden in the proximity of the city by King Peter II of Aragon in 1342 B.C. Since then, rice cultivation was repeatedly prohibited and tolerated because the population was reluctant to abandon the crop in the absence of suitable replacements. The prohibitions of 1403 and 1483 were particularly severe. King Don Martin, who attributed a deadly epidemic and the decline of the population to rice cultivation forbade it in 1403. King Don Alonzo in 1483 made rice growing a capital offense.

The sequence of prohibition and tolerance was sustained by a continuous controversy over the supposed benefits of rice and its dangers to public health. Some argued that the infection of the air could not possibly originate from the rice plants themselves, but from the nature of the land. They believed that in swamps and marshes, which are unsuitable for other crops, rice was not only economical but beneficial to public health. They reasoned that land preparation and irrigation circulated stagnant water and prevented disease. The controversy became particularly open in the 18th Century, when it attracted the interest of natural scientists (Riera 1983). In the second half of the century, King Ferdinand VI ordered the planting of rice in swamps as a sanitation measure, and finally in 1789 rice cultivation was regulated in Valencia.

The Memoires of the Royal Medical Academy of Madrid in 1797 record the observations of Dr. Antonio Josef Cabanilles in which he recognized the benefits of rice cultivation in swamps, but stressed the general health risk it posed and recommended that, even in swampy areas, rice should not be grown close to villages. He recommended prohibiting rice cultivation in all areas suitable for other crops, arguing that its irrigation requirements made it uneconomical in such areas.

Cabanilles also described the general epidemiological picture of fever in the coastal area. He attributed fever to the excrement and dead bodies of insects in the swamps mixing with salt from the sea.

Cabanilles noted that there was practically no disease in winter, but in spring, tertian fevers appeared and in autumn they became continuous, malignant, and pestilential. He also observed that foreigners were more seriously attacked, noting that they “carry to their homes the poison which will kill them” (Villalba 1802).

There are many other examples regulating rice cultivation because of its observed association with disease, e.g., provincial ordinance in Tucuman, Argentina, in 1813 (Boyd 1949), but the Valencia story illustrates important epidemiological points.

Early control approaches

Since the discovery of the transmission cycle of malaria and the beginning of scientific malaria control, ricefields have received special attention. Numerous epidemiological, entomological, and ecological studies have been done and many efforts to control either mosquitoes in general, specifically *Anopheles,* or malaria transmission have had varying degrees of success. The partial interpretation of such studies has sometimes produced apparently contradictory conclusions.

Before the advent of residual insecticides, malaria control rested on three main approaches:

1) the wide distribution of antimalarial drugs and the promotion of early treatment and chemoprophylaxis in highly endemic areas;
2) the emphasis on mosquito control, sanitation, and reduction of human-vector contact; and
3) integrated rural development incorporating health facilities and environmental sanitation with economic planning.

All of these approaches were used in various combinations in different areas and gave rise to the formulation of reasonably standard methods of control, which included: 1) prevention of human-vector contact, 2) source reduction, 3) improved diagnosis and treatment, and 4) limited use of insecticides against adult mosquitoes.

The development of scientific malaria control coincided with and supported colonial and economic expansion of developed countries. That provided not only an increasing demand on the skill and the imagination of malariologists, but an abundance of problems requiring solutions.

Malariologists were at the forefront of awakening political concern about the socioecological impact of economic development in rural areas.

Rice remains the most widely irrigated crop grown throughout the malaria-infested world. Ricefield malaria was a prototype of health problems associated with irrigation. The water requirements of irrigated rice and expansion of irrigated rice culture led to the development of water management methods.

Sir Gordon Covell said: "It is imperative that every new irrigation project shall include provision for adequate drainage, and also that no such project shall receive sanction without previous scrutiny by the health department concerned. The latter principle should be applied not only to irrigation projects, but to the engineering schemes of all descriptions" (Boyd 1949). That recommendation is valid today.

Water management required attention to the entire irrigation system, including the construction and maintenance of impoundments, distribution and drainage canals, as well as of water manipulation and the use of larvivorous fishes or chemical larvicides. The economic value of irrigation water was seen as the point where the interests of malariologists and managers converged for the promotion of appropriate water management (Hill and Cambournac 1941). Among various water management techniques, intermittent irrigation appeared most suited to the control of ricefield malaria. Intermittent irrigation requires the periodic drainage of irrigation water to dry the soil surface (Knipe and Russell 1942). The method was derived from observation of the advantages of frequent interruptions in areas where water had a high economic value, even if it was often irregularly practiced (Hill and Cambournac 1941). Success requires rigid control of the wet and dry periods. Dry periods should correspond to the time required for larval development by vector species (Russell et al 1942, Kiker and Knipe 1949).

Intermittent irrigation not only effectively controlled malaria (Hacket 1937, Hill and Cambournac 1941). Contrary to what many people feared, it did not reduce the grain and straw yields; sometimes it even increased them (Russell et al 1942). Nevertheless, intermittent irrigation seems to have been used only sporadically outside the USSR, where large-scale use was recommended in 1940 by the Commissariat for Public Health and the Commissariat for Agriculture to prevent malaria in rice-growing regions (Boyd 1949). The recommendations required health boards to supervise the selection of new areas for rice growing and mandated that new ricefields cover large areas suitable for aerial control of *Anopheles* larvae.

Intermittent irrigation was still in its infancy when residual insecticides presented an irresistible appeal to malaria control planners. DDT indoor spraying has overshadowed all other control methods since the 1950s when it was shown that DDT could economically eradicate malaria over large areas.

Most malaria eradication campaigns in the 1950s and 1960s included rice-growing areas within the total-insecticide-coverage strategy, with various success. Although ricefields are not epidemiologically uniform, control was often better than in other agricultural areas in the tropics.

General epidemiology of malaria in rice-growing areas

Rice growing today is not associated with the most serious malaria problem areas of the world, although ricefields still produce the highest densities of anophelines. The most serious malaria problems, outside of tropical Africa, are not so much those of persistence or resurgence of transmission in old problem areas, but the creation of new malarious areas in new agricultural or mining developments. These areas attract new populations and the mobility of those populations poses serious control problems. An even more serious problem is presented in areas of social or political disturbance or of illegal trade, which often concentrate in border areas. There the epidemiological impact affects several countries.

Irrigated rice-growing areas generally have a higher degree of economic and social organization not found in the early colonization of jungle areas. Moreover, their inhabitants, because of their higher social development, are less willing to tolerate malaria and even mosquitoes. They often demand and contribute to the control effort.

Nearly 90 yr of malaria control plus recent studies indicate great variability in the epidemiological situation, despite apparent similarities in the general ecology.

Variability of malaria epidemiological patterns

Variations in malaria epidemiological patterns are caused by three important factors: 1) the ecological impact of rice cultivation, 2) response to control, and 3) human ecology.

Ecological impact of rice cultivation

The introduction or extension of irrigated rice produces major ecological impacts. First, there is an enormous increase in mosquito breeding surface. Second, the increase selectively favors some species, and often changes the relative predominance of or the displacement of certain vector species or genotypes. The result is marked changes in the equilibrium of malaria transmission in the area, which may increase or decrease in relation to the vectorial ability of the favored genotype.

Surprisingly, tropical ricefields are often free from dangerous anophelines. Innumerable stagnant ricefields in the plains of Assam were reported almost free of the local vector, *Anopheles minimus,* and large ricefields in Malaya were equally free of *A. maculatus* (Muirhead-Thomson 1951).

A. gambiae ssp. has been studied recently in rice-growing areas in West Africa. *A. gambiae* and *A. arabiensis* in Nigeria show microgeographical variations in chromosomal inversion frequencies with similar high frequencies of a specific genotype in widely separated rice-growing areas (Coluzzi et al 1978). In Burkina Faso, despite *A. gambiae* human-biting densities 4 times higher than average, malaria transmission was 4-10 times lower. Actually, a negative correlation was observed between human biting density and intensity of transmission in the rice-growing area. Moreover, *A. funestus* and *A. nili* do not proliferate in the rice-growing area. Cytogenetic studies (Robert et al 1986) showed that the karyotype Mopti of *A. gambiae* is practically the only one (98%) found at the centers of ricefields. The rare form Savana was twice as frequent at the periphery than at the center of ricefields. *A. arabiensis* was five times more frequent at the periphery. The authors suggest that increased densities favored those genotypes that developed rapidly and had short life expectancies. High density may also favor the transmission of mosquito pathogens, which may contribute to short life expectancy. A greater attraction of parous females to animals may account for their greater dispersion toward the periphery of ricefields (Coluzzi et al 1984, 1985).

Similar species displacement may have operated in the coastal areas of Valencia, where an effective vector (possibly *A. labranchiae*) may have been progressively replaced by a poor vector (*A. atroparvus*) or a nonvector species (*A. melanoon*). *A. labranchiae* has not actually been recorded in Valencia, but records show that in the last 50 yr it has disappeared from where it was formerly distributed over limited areas further south on the Mediterranean Coast (Blazquez and de Zulueta 1980).

In contrast, in a 1000-km^2 area of the Ruzizi Valley of Burundi, an area of unstable malaria transmission, endemicity was considerably higher and more stable in the rice-growing areas (Coosemans et al 1984). *A. arabiensis* and *A. funestus* are the main vectors and *Plasmodium falciparum* the predominant parasite. Similar observations in Afghanistan showed the highest incidence of malaria in irrigated ricefields, where most of the population live (Duhanina et al 1975).

Many forms of epidemiological adaptation may occur between these extremes. Malaria transmission occurs in malaria-free areas when imported cases coincide with the irrigation season in rice-growing areas, such as in Iraq (Shihab et al 1984) and in California (CDC 1974). The periphery of a predominantly ricefield biotope may be invaded by more aggressive vectors from surrounding areas. In some areas of the Indochina peninsula, ricefields close to foothills are affected by *A. minimus* or *A. maculatus* which breed in foothill streams near the ricefields. Even if *A. campestris* or *A. aconitus* are controlled in ricefields, the inhabitants may be infected by *A. dirus* when they venture to nearby forests.

Response to control

Irrigated ricefields are commonly protected from pests by insecticides, frequently by aerial application. As a consequence, malaria vectors in these areas have a high degree of resistance to various insecticides. On a global scale, the intensity of resistance and the spectrum of multiresistance to insecticides in malaria vectors of rice-growing areas is second only to that of the main vectors in cotton-growing areas *(A. albimanus, A. stephensi,* and *A. sacharovi).*

Resistance often extends to most of insecticides available for malaria control. Many vectors also exhibit exophilic behavior or high excitorepellency. High resistance and excitorepellency in the same population are not uncommon because the selection for resistance is due to crop protection and not to indoor spraying. Such situations have been documented in *A. sinensis* in China, in *A. aconitus* in Java, in *A. culicifacies* in Burma, and in *A. culicifacies* and *A. nigerrimus* in Sri Lanka (Herath et al 1986). Similar degrees of resistance have been found in potential malaria vectors in South Korea. Resistance to DDT and exophily have also been found in *A. hyrcanus* and high irritability by DDT and exophily in *A. pulcherrimus,* the main vectors in rice-growing areas in Afghanistan (Artemev et al 1977).

Although insecticide spraying is ineffective against multiresistant vectors, good malaria control, and even mosquito control, has been obtained by integrated control measures including improved diagnosis and treatment of malaria. Predator fish larvicides, and source reduction by improved maintenance of canals and drainage have successfully reduced vector populations. In China, control has been achieved by farming edible fish of the carp family in ricefields, and treating drains, wells, ditches, and small bodies of water with *Gambusia affinis holbrokii.* Grass carp and common carp not only provide a rapidly developing protein source but also are reported to increase rice yield (Honan Provincial Antimalaria Experimental Working Group 1977, Luh and Laird 1981). Some species of indigenous larvivorous fish, such as *Aplocheilus latipes,* have been used for mosquito control in South Korea (Yu et al 1983).

Human ecological factors

New irrigation projects are likely to affect human ecology by attracting new settlers or laborers, by establishing new systems of trade, and by changing land values, which may change the distribution of ownership and occupation. The effect of these changes on malaria transmission varies considerably, not only between different areas but within an area at different times. For example, in coastal Guyana, the vector *A. darlingi* was eliminated and malaria was eradicated. Irrigated ricefields were extended into neighboring pasturelands, mechanization replaced working animals, and the coastal population lost its immunity. Meanwhile, migrants from the interior brought malaria parasites to the coast and finally, *A. aquasalis,* breeding in neighboring salty marshes, produced a malaria epidemic (Giglioli 1963).

Attraction of nonimmune settlers to newly opened irrigated land has been a problem in the Mahaweli development scheme in the endemic dry zone of Sri Lanka. Social problems may result from changes in traditional attitudes and working relations. In established irrigated lands in Sri Lanka, ownership of the irrigation system progressively changed from local communities to government or individuals. The subsequent weakening of traditional community pressure for maintenance of the tanks, canals, and ditches resulted in a multiplication of vector breeding (Ault 1983). Attraction of labor and the building of temporary shelters near ricefields have been reported as a problem in Zanzibar (Chopra 1968).

In Central Java, Indonesia, cattle are kept separate from human habitations, thus considerably reducing human-vector contact. There, the relatively minor effect of spraying DDT against highly resistant *A. aconitus* greatly reduced transmission (Verdrager and Arwati 1975).

Present malaria control approaches

The Eighteenth WHO Malaria Expert Committee in 1985 recommended that the design of malaria control should be based on:

Total population diagnosis and treatment

Total population coverage should include, at minimum, facilities for diagnosing and treating fever, which are accessible to the entire population. These facilities should be integrated into the primary health care infrastructure, and should be supported by a referral system capable of managing the treatment of severe malaria cases and the differential diagnosis of cases that fail to respond to treatment at the periphery. The referral system should be the basis for monitoring the spread or intensification of parasite resistance to antimalarial drugs. This infrastructure should also provide the mechanism for promoting individual or community protection against malaria transmission. It should also be the basis for developing epidemiological services to guide the application of more complex solutions to specific problems.

This attention to the disease problem posed by malaria is a necessary response to obvious population needs. Malariologists must ensure that the population receives the best possible response. In many malaria endemic situations, it may serve as a port of entry to primary health care.

Selective transmission control

Malaria transmission control should be applied to well-defined objectives with particular emphasis on sustainability even if progress is slow. Planning, implementation, monitoring, and evaluation must be guided by competent technical personnel.

The selection of place and timing of specific control intervention requires basic epidemiological services, which should have been developed as part of the referral system of the health infrastructure. It is essential to avoid, as much as possible, specialized operational structures, which may persist as vertical services. Whenever specialized services are necessary, they should have the capacity of future development into multidisciplinary epidemiological services.

The simplest objective for such services is the control of epidemics. Further developments could provide improved systems for recognizing high-risk situations, evaluating malaria endemicity, stratifying the malaria problem in terms of its health and social impact, forecasting and preventing epidemics, and controlling malaria transmission in highly endemic areas and eventually throughout the country.

These systems should be able to plan antimalaria activities according to local situations, assessing relevance, feasibility, and affordability based on the best local epidemiological knowledge available. This epidemiological approach is the basis of the malaria control strategy, approved by the World Health Assembly (WHO 1978) and further elaborated by the WHO Expert Committee and Study Group on Malaria Control as part of primary health care (WHO 1984, 1986).

Epidemiological approach to malaria control

The epidemiological approach to malaria control involves consideration of the following principles:

- Local variability must be evaluated not only in relation to its intensity, but also by its response to control interventions.
- An epidemiological situation is a temporary state of an ecological system more or less resilient to changes in its determinants.
- Any epidemiological system tends to return to its previous state of equilibrium when interventions are discontinued, unless a new state of equilibrium has been or can be reached.
- A capacity should be developed to estimate the type, intensity, and duration of interventions that lead to more favorable states of equilibrium.
- Response to control interventions depends on complex, multiple, interrelated causes, which do not permit the direct transfer of experience. The conditions of transferability should be studied and documented.
- Malarious areas must be characterized in terms relevant to the selection of feasible interventions.

The selection of the main control approaches should be based on the epidemiological problem and the stage of development of the area to which they will be applied. The need for treating cases must be distinguished from the potential for integrated vector control. These require technical competence and management (Mather et al 1984), adequate money, and sustainability (Lichtenberg and Getz 1984). It may be thought that if malaria were eradicated, treatment facilities would be superfluous. That would be true if success could be assured. However, experience shows that if eradication fails after years of heavy expenditures, countries may be left with a costly and ineffective vector control service and inadequate capacity to treat disease.

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Author's address: J. A. Najera, Malaria Action Programme, World Health Organization, 1211 Geneva, Switzerland.

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Control of schistosomiasis: research aspects

N. R. BERGQUIST AND CHEN MING-GANG

Human schistosomiasis is discussed emphasizing the difference between infection and disease, and strategy for control of transmission and morbidity is reviewed with special reference to rice production and irrigation schemes. Indirect techniques for diagnosis such as chemical reagent strips and detection of specific antibodies are discussed in relation to parasitological diagnosis and novel techniques relying on the detection of circulating antigens. The possibility of developing a schistosomiasis vaccine is commented on and an overview of currently available antigens for immunological intervention is presented.

Human schistosomiasis presents a complex life cycle involving alternatively parasitic and free-living stages. It is a trematode infection transmitted to humans through an intermediate stage released from infected freshwater snails belonging to the subclasses of the *Pulmonata* or *Prosobranchiata.* The adult stages are sexually differentiated worms, which inhabit the venous plexa around the lower intestine or the bladder. Their life span has a mean range of 4-8 yr. There is no multiplication inside the human host, so the parasite load is acquired by multiple infections.

Humans are affected by five epidemiologically distinct species: *Schistosoma haematobium, S. mansoni, S. japonicum, S. intercalatum,* and *S. mekongi,* but only the first three are widespread. *S. haematobium* causes urinary schistosomiasis; the other four species cause the intestinal form of the disease. It is estimated that 500-600 million persons are exposed to the infection and that more than 200 million are infected (WHO 1985). Except for *S. japonicum,* where animal reservoirs contribute significantly to human transmission, there is no evidence that animals play a significant role in transmitting human schistosomes.

The infection has a chronic and complicated course, the parasite load being the main determinant of its seventy. Surprisingly, the adult worms play essentially no role in the pathology, the reaction to eggs retained in the tissues of the human host being responsible for the symptoms, which underscores the difference between infection and disease. The four stages of schistosomiasis are shown in Table 1.

Invasion and maturation of the parasite constitute the first two stages of infection. Symptoms are usually mild and general, but occasionally more severe reactions, described as acute schistosomiasis, occur. These stages are difficult to

Table 1. Four stages of schistosomiasis and their parasitological, clinical, and pathological characteristics.

Stage of disease	Parasitological characteristics	Clinical characteristics	Pathological characteristics
Invasion	Penetration Migration to the lungs	Skin reactions Fever and coughing (not always present)	Papular dermatitis Lung and liver inflammatory reactions
Maturation	Migration to definitive sites Early oviposition	Acute ferbrile illness, not always recognized or present	Hyperergic reactions to products of eggs and/or schistosomula
Established infection	Oviposition accompanied by excretion of eggs	Hematuria or intestinal and other digestive symptoms	Focal inflammatory granulomatous reactions to eggs
Late infection and complications	Prolonged infection with reduced or discontinued oviposition	Portal hypertension, cor pulmonale, obstructive uropathy and renal failure	Vascular and fibrotic lesions of variable degree in various organs

Source = WHO 1985, Table 4, p. 30.

identify in the endemic areas where disease rather than infection is the stage of major concern. Once infection is established, hematuria or intestinal bleeding due to penetration and retention of eggs in the wall of the gut and bladder may occur. Later, scarring reactions produce symptoms due to mechanical obstruction, primarily in the liver and, in the case of *S. haematobium* infection, in the urogenital system.

It is important to recognize the distinction between light and heavy infection because the clinical symptoms of schistosomiasis are essentially confined to the heavy infection.

Diagnosis

Epidemiological and community studies of schistosomiasis rely on the demonstration of eggs in urine for *S. haematobium* and in feces for the other species. The diagnostic techniques are used not only for detecting infected persons but also for distinguishing between light and heavy infections. Quantitative diagnosis is necessary to evaluate the effect of control measures and for a correct epidemiological interpretation of the disease situation. Most studies agree that only higher egg counts correlate significantly with the presence of serious morbidity such as enlargement of the liver and spleen.

In intestinal schistosomiasis, the eggs in a small measured amount of feces under a cellophane film on a glass slide are counted (Kato and Miura 1954, Komiya and Kobayashi 1966). Patients may be divided into 3 categories according to the egg counts obtained by a template that holds 41.7 mg of feces (Katz et al 1972). The eggs of *S. haematobium* may be detected microscopically and quantified after concentration by filtration of urine (WHO 1985, p. 49).

Table 2. Classification of intestinal and urinary schistosomiasis infections based on egg counts in feces and in urine.

	Intestinal schistosomiasis	
Eggs/gram of feces	Classification	*Hepatomegaly*
24-96	Light	Rare
120-792	Moderate	Frequent
>816	Heavy	Always present
	Urinary schistosomiasis	
Eggn/10 ml of urine	Classification	*Hematuria*
1-49	Light	Frequent
>50	Heavy	Always present

Source = WHO 1985, p. 49-50.

Due to destruction of tissue lining the bladder, individuals heavily infected by *S. haematobium* may be identified by simple, indirect diagnostic techniques relying on reagents sensitive to hemoglobin and protein. Chemical reagent strips have been evaluated for sensitivity and specificity for the detection of urinary schistosomiasis in different age groups of patients (Feldmeier et al 1982, Wilkins et al 1979). A high proportion of children excreting more than 50 eggs/10 ml of urine are found to have hematuria and proteinuria, making a division into two groups the most advisable. The details of the different patient groups are depicted in Table 2.

High standards of microscopy must be maintained, particularly when conducting prevalence studies in areas of low transmission. Because of the relatively low sensitivity of direct, parasitological diagnostic techniques, quality control is of special importance when, as a result of control, individual worm loads decrease and infections become less frequent. However, unless they are specially stained, the excretion of old, nonviable eggs associated with a successfully treated infection cannot be microscopically discriminated from those emanating from reinfection, thus prolonging the time for a definite assessment of prevalence after treatment.

Serological techniques that rely on the detection of antibodies directed against *Schistosoma* antigens can be used diagnostically in individuals who migrate from nonendemic areas into endemic areas, but are of limited value in the endemic situation. Their role should be compared with the simple, quantitative, direct parasitological techniques used in current schistosomiasis control programs. An international collaborative study of antigens for immunodiagnosis of schistosomiasis supports the conviction that there is no available antigen or test system better than current direct parasitological techniques for identifying active infection (Mott and Dixon 1982). However, serological methods could be useful as an adjunct to microscopy in successful control projects or in areas of low endemicity.

The lack of methods for the production of large amounts of purified and well-characterized *Schistosoma* antigens has hampered the development of reliable and sensitive indirect antibody techniques. However, the advent of recombinant DNA technology has removed this constraint and promising diagnostic antigens have already been cloned and produced on a large scale (Klinkert et al 1987). Current serological techniques are not, however, suitable for monitoring control efforts because titers do not start to decline until 1-2 yr after successful treatment. It remains to be seen if the identification of stage-specific pure antigens will improve this situation.

Presumably, only the determination of antigens secreted or excreted into the bloodstream of the host would allow a reliable indication of an ongoing infection. Although a number of antigen detection techniques have been devised, there are methodological difficulties that must be mastered before this approach can be seriously considered for routine implementation. Circulating schistosome antigens have been classified according to their electrophoretic mobility (Deelder et al 1976), but each antigen exists, even in heavy infections, in only minute quantities requiring a high degree of specificity as well as sensitivity of the detection system used. Employing monoclonal antibodies (MAbs), researchers are currently addressing these questions and investigating the chemical nature of target antigens. A majority of these seem to be polysaccharides (Cashier 1980). Correlations between worm burdens and serum concentrations of antigen have been reported (Feldmeier et al 1986, Nogueira-Queiroz et al 1986). Based on recent developments, it seems safe to assume that a superior alternative to parasitological diagnosis is within reach.

Epidemiological aspects

Certain communities within a confined geographic area may have a high prevalence of schistosomiasis, whereas nearby communities can be practically free of the disease. This focal distribution of schistosomiasis is an important characteristic of its epidemiology, which is influenced by variables relating to the parasite, the intermediate host, and the human population. The measurement of the incidence of new infections is hampered by the uncertainties attached to parasitological diagnosis and the long natural duration of infection. In endemic areas, virtually all children will eventually become infected, and there is a real possibility that conversion from an apparent uninfected state to one of egg excretion only reflects the maturation of a recent infection or an increase of the worm burden.

Information on prevalence gains in significance if it is supplemented by information on the intensity of the infections inasmuch as prevalence rates are directly related to the intensity of infection, which, in endemic communities, generally increases with age until adolescence and then declines. There is, however, a difference between types of infection in that intensity of infection and prevalence decrease with age-earlier in *S. haematobium* infections than in *S. mansoni* infections. In *S. mansoni* infection, prevalence also tends to abate more slowly than does intensity. Variations in this general pattern occur in areas of high transmission, and with varying degrees of decline in older age groups depending usually on the extent of water contact and parasite species. There is increasing evidence that the agedependent declining prevalence of infection can be attributed to the development of immunity, but the mechanisms are not yet fully understood.

Apart from the autochthonous population, schistosomiasis affects workers and their families and other migrants as a result of water resource development schemes. Schistosomiasis transmission may or may not be established in any of these groups.

If schistosomiasis is initially absent in the autochthonous population, subsequent surveillance of this group will provide a sensitive indicator of its introduction.

Comparisons between disease distribution and intensity have been made in areas before and after development. The following examples underline the enormous impact of irrigation projects on disease prevalence. Within 3 yr of construction of the Low Dam at Aswan, Egypt, *S. haematobium* infections increased from a mean prevalence of 6.5% to close to 60% (WHO 1985). Irrigation of the Gezira, Sudan, by the construction of the Sennar Dam in 1924, and extension of the system after 1950, have resulted in an increase of the prevalence of *S. haematobium* infection from less than 1% in the period 1924-44 to 21% in adults and 45% in children in 1952 (WHO 1985). In Ghana, *S. haematobium* prevalence rates were more than 90% in children aged 10-14 in some lakeside communities of Lake Volta compared to 5-10% before the area was impounded (WHO 1985).

Current control approaches

The current strategy of schistosomiasis control is aimed at its morbidity or disease (WHO 1985). This strategy is based on chemotherapy using the safe and effective drugs that have recently become available for treating all types of human schistosomiasis. Oxamniquine, metrifonate, and praziquantel in particular are now used on a large scale in most endemic countries. Rather than indiscriminate mass treatment or prophylaxis of entire populations in endemic areas, treatment of infected patients after diagnosis is recommended.

The current emphasis on treatment of infected people does not preclude other control measures. On the contrary, snail-control measures undertaken immediately preceding, or concurrently with, large-scale use of chemotherapy can be expected to reduce transmission, and intensity of infection in the population. Molluscicidiing primarily interrupts transmission and should be undertaken at sites where transmission is most likely. That requires specialized personnel for maximum effectiveness and realistically should aim at controlling, rather than eradicating, snails. High costs and toxicity to other fauna and to plants are the main limitations of molluscicides, but so far their use has not resulted in resistance. Chemical compounds are generally used, but plant molluscicides are currently the focus of research (Mott 1987).

The potential of biological control has had wide appeal to field biologists, but no practical method has yet been evaluated sufficiently to be recommended. Suggested methods include the use of agents that are infectious to snails, predators, or competitors such as *Marisa cornuarietis* or *Heliosoma druryi, Marisa* has received most attention although its use is still controversial and in need of more research. The danger to rice seedlings has been exaggerated but the snail is not particularly resistant to drying out of its habitat during prolonged periods (Nguma et al 1982).

Public awareness of schistosomiasis may emerge slowly because the onset of the disease is usually insidious and serious clinical manifestations appear slowly. Educating populations involved in rice production on their role and relationship to schistosomiasis should be given the highest priority. Schistosomiasis prevention might best be taught if the community, including schoolchildren, recognize that parasitic diseases are caused by their own habits. Rice irrigation schemes provide a unique situation to reinforce education concerning vector-borne diseases.

During the planning phase of a project the level of population migration into the area is usually predicted. If it is assumed that the new population will come from an endemic area, a program of screening and treatment in health facilities in the area of origin and in the project area may prevent the introduction of schistosomiasis or of new species of schistosome into the project area. Likewise, workers employed in water-resource development projects and their families should be screened and treated if infected. Selective chemotherapy of infected groups at the early stages of implementation could reduce costs considerably.

All vector snails require water, at least for breeding. The management of water bodies is therefore, a potentially powerful control method. In the ricefield environment there are opportunities for vector control by changing the aquatic habitat of the snail. These must be viewed, however, in conjunction with farming requirements to achieve maximum crop production. The prevention of unnecessary human contact with cercariae-infested water is an integral component of any schistosomiasis control scheme, but opportunities for this approach in rice production areas are limited. However, infection does not take place primarily in the ricefield itself, but in canals and surrounding living quarters. Overall infection levels in settlements can be reduced by siting housing away from canals; providing an adequate, safe water supply and sanitation; protecting surface water by covers, pipes, or fencing; and providing protected facilities for bathing, laundering, and recreation. A control program that is integrated into the rice production process and based on environmental management of man-made vector habitats minimizes breeding while creating minimal or neutral effects. Environmental management in the past relied heavily on structural devices and mechanical equipment such as canal lining and storage tanks. These engineering approaches will continue to play an important role in large irrigation schemes. However, the smallholder rice farmer, faced with high production costs and unable to apply such engineering methods, must also be involved in schistosomiasis control.

Adequate and acceptable means for excreta disposal are important to control schistosomiasis. If the feces (or urine for *S. haematobium*) of infected individuals do not reach water, then neither do the eggs and the disease cannot be transmitted.

Immunological intervention

There is now sufficient evidence to indicate the presence of, at least a partial, acquired immunity to human schistosomiasis (Butterworth 1987, Wilkins et al 1987). This and the reproducible induction in animals of protective immunity, with attenuated parasites and with antigenic preparations, indicates that vaccination against schistosomiasis is achievable and that the extension of this to humans is a realistic goal. Even a vaccine with only partial efficacy would have potential value if used in conjunction with other control measures, particularly with the highly efficaceous drugs already in use.

An understanding of the immune effector mechanisms in relation to schistosomiasis has come from the use of experimental animals. Apart from immunization with genetically engineered antigens, resistance to infection can be induced, in permissible animals, either by irradiated cercariae or by attenuated larvae (schistosumala). A majority of the exposed epitopes of the young schistosomulum, recognized by antibodies from rats and chronically infected mice, are carbohydrates that cross-react with schistosome egg antigens. Polypeptide epitopes appear to be preferentially recognized by antibodies from mice immunized with irradiated cercariae. They do not cross-react with egg antigens but are shared with the surface membrane of the adult worm. These antigens and evidence for their role in immunity have been determined by experiments with MAbs. Several hundred specificities have been produced and some MAbs confer partial resistance when passively administered to experimental animals. Protective MAbs recognizing carbohydrate epitopes expressed on high molecular ratio (M_r) glycoconjugates of schistosomal origin and also on a M_r38 kilodaltons (K) molecule from the parasite have been reported (Kelly et al 1986). However, most of the target antigens have not been analyzed beyond determining their molecular size.

Homogenates of various schistosome stages have been inoculated in mice intradermally with bacillus Calmette-Guerin resulting in antibody-independent T-cell responses (James et al 1985), and subcutaneously with saponin, which resulted in both antibody and delayed-type hypersensitivity responses (Simpson et al 1987). An immunoglobulin E response was induced when cercarial antigens were injected together with alum (Horowitz et al 1982). These approaches have given levels of protection comparable to immunization with irradiated cercariae. A 27-38% reduction of worm burden compared to control was achieved using M_r 22K and M_r 28K antigens derived from the schistosomulum surface (Harn et al 1987); high levels of protection have also been reported with paramyosin, a M_r97K molecule produced by genetic cloning (Lanar et al 1986). In the rat, a mixture of M_r22-26K antigens released from young schistosomula in culture gave nearly 90% protection, even without added adjuvant (Aurault et al 1985). More than 75% protection was achieved by immunization with an anti-idiotype antibody raised against a MAb, recognizing the M_r 38K antigen (Grzych et al 1985). In addition, there are promising results from immunization of primates as evidenced by work with *Cynomolgus* monkeys using a M_r 155K surface antigen (Smith and Clegg 1985). Highly expressed, developmentally regulated genes that encode the precursor protein for the schistosome eggshell have also been cloned, thereby providing a possible alternative strategy for prophylaxis by interrupting oogenesis.

The large-scale production of antigens for a vaccine will have to be done through hybridization of the relevant schistosome genes with the genome of rapidly dividing microorganisms such as *Escherichia coli* or *Vaccinia.* An impressive number of schistosome gene libraries have been developed. Collectively, they represent most stages of the life cycles of the three major species of human schistosomes.

The results in the area of vaccination can be viewed as positive, but the incomplete degree of protection so far achieved in experimental animals is an obvious limitation. However, acceptable levels of protection can be achieved by the combination of various methods and antigens. The next step will be to demonstrate the induction of protection with antigens produced in vitro or synthesized in vivo within a recombinant infectious organisms such as *Vaccinia* virus or attenuated *Salmonella* spp. The biological characteristics of the parasite, particularly the lack of reproduction in the definitive host and the apparent absence of antigen variation or diversity, support the feasibility of developing an effective vaccine.

Conclusion

Although the work toward a schistosomiasis vaccine is important, it is premature to speculate about its possible role for control, nor should it be forgotten that schistosomiasis control is already feasible with presently available tools. However, it is particularly difficult to control a disease at the same time the environment is being transformed in a way that promotes an increase in the transmission of that disease. Diagnosis and treatment in general health services must be provided from the outset to prevent establishment of transmission, as has been successfully done in water resource developments in southern Brazil. Budgets for supplies, equipment, and drugs for control of schistosomiasis and other diseases should be included at the planning phase of irrigation schemes. Applied field research focusing on separating humans and the snail host could bring about much-needed improvement in the design of irrigation projects, particularly those for rice production. Although an infrastructure for disease control can reduce specific risks, less dramatic problems such as those dependent on the deterioration of human living conditions may be ignored. Preventive measures, implemented sufficiently early, will require fewer personnel, less equipment, and less material than if the breeding areas of disease vectors or intermediate hosts are allowed to develop and the prevalence of diseases to increase. Schistosomiasis control within rice irrigation schemes is a challenge and must involve intersectoral coordination at all stages. Health delivery systems in most endemic areas can implement control effectively with adequate personnel and finances.

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Notes

Authors' addresses: N. R. Bergquist, UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases, 1211 Geneva 27, Switzerland; Chen Ming-gang, World Health Organization, 1211 Geneva 27, Switzerland.

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Schistosomiasis in the context of rice production systems in developing countries

N. R. BERGQUIST, CHEN MING-GANG, and K. E. MOTT

The impact of disease and of water irrigation schemes are discussed in general terms including specific references to the epidemiology of schistosomiasis. Brief reports of schistosomiasis prevalence and control strategies with special regard to rice production in different parts of the world are presented. Case reports are sorted according to the WHO regional classification: Eastern Mediterranean, Africa, Southeast Asia, and the Western Pacific.

Irrigation continues to be the principal means by which humans modify their environment to increase food supplies. Developments in irrigation technology and agronomy have increased the potential productivity and profitability of agriculture considerably. In 1984 about 15% of the total cultivated areas of the world relied on irrigation, and those lands contributed more than 40% to the total production of crops. Of the 220 million ha of irrigated land in the world, almost half are in Asia, and a major portion is planted to rice (IIED and WRI 1986, 1987).

Unfortunately, irrigation schemes in tropical and subtropical regions create ecological environments favorable to vector-borne diseases. The surface flooding and soil saturation specific to ricefields provide an ideal environment for many vectors, particularly those of malaria and schistosomiasis. The expansion of rice production in the developing world almost assures an increased transmission. Without strict controls, this secondary effect of irrigation is far from negligible. In fact, inhabitants in endemic zones are deprived of much of the fruits of their labor by increased morbidity due to a higher transmission of parasitic infections. Adding to the magnitude of the problem, irrigated land is increasing at an annual rate of 1.5% (IIED and WRI 1986, 1987).

The social and economic significance of schistosomiasis depends on the conditions influencing its transmission and on the resources invested in health-promoting systems, including related sectors such as housing, water, and sanitation (Rosenfield et al 1984). The frequency of transmission in a population, the proportion of those infected who will develop serious symptoms, the duration and nature of the disease, and fatalities are all important parameters. An estimate of days of healthy life lost due to disease or premature death may be used to evaluate the importance of a disease (Morrow 1984). Although this is a crude measure, it allows ranking the impact of various infections, thereby providing a base for policy decisions. Estimation of days lost may also be used to compare cost-effectiveness of different strategies for prevention of a specific infectious disease. High benefit-cost ratios for schistosomiasis control have been shown by Farooq (1963) in the Philippines and by Chen et al(1982) in China.

Schistosomiasis and rice production

Rice growing necessarily includes environmental modifications that, unfortunately, tend to create habitats suitable for the snail intermediate hosts of schistosomiasis. For this reason, rice farmers and those living near ricefields are exposed to greater risks of infection than those working or living away from the fields. As the use of water increases, it is to be expected that water-related infections in general and schistosomiasis in particular will become increasingly prevalent.

Irrigation systems in tropical zones quickly become inhabited by snail intermediate hosts. It is clear, however, that for economic reasons, irrigation schemes will not be abolished because of that alone but will continue to expand. Despite their agricultural benefits, small impoundments may carry even greater health risk since they are normally constructed without any health care measures. Such impoundments, usually privately financed, lack maintenance, sewage, and water discipline, all of which favor schistosomiasis transmission. Drinking water supply deserves special mention although it does not constitute a major route of infection in schistosomiasis. Sites of human-water contact play an important role in transmission because collecting water presents a distinct risk of infection. Fortunately, household water can be easily treated against cercariae by storing it for 48 h. Cercariae die if they do not penetrate a host within that length of time.

The continuous expansion of rice growing into endemic areas as well as intensified cropping in traditional areas, including the cultivation of peri-urban land, are coupled with socioeconomic changes in many of the farming communities. That demands a control strategy that forms an integral part of the rice production process. Adequate planning, establishment, and management of irrigation schemes that incorporate health measures and environmental safeguards are necessary to real economic and medical progress. This paper details the seriousness of the schistosomiasis situation and identifies areas in which research and control could be made most effective.

Case studies

Eastern Mediterranean Region

In the Eastern Mediterranean region, irrigated rice cultivation is generally not a major agricultural activity. The following case studies deal with schistosomiasis in irrigated agricultural areas.

Egypt. Egypt has one of the oldest continuous irrigation systems in the world as well as the earliest records of endemic schistosomiasis. The extent of irrigation is unparalleled in other countries (Mobarak 1982). The control of schistosomiasis in several of these irrigation schemes has been thoroughly reviewed (WHO 1985). The advent of large-scale chemotherapy through the rural health care system—96% of rural Egyptians live within 5 km of a health unit—is having a significant impact on the prevalence and intensity of schistosomiasis in most of the areas where support for agricultural development has included schistosomiasis control (Mobarak 1982). The control of schistosomiasis in Egypt represents a long-term challenge.

The Aswan High Dam markedly altered the dynamics of schistosomiasis transmission in Upper Egypt (Hammam et al 1975) as well as in the Nile Delta (Malek 1975). The traditional basin system of irrigation was transformed into perennial irrigation. In Upper Egypt, the prevalence of *Schistosoma haematobium* infection in a village using basin irrigation was 3%; prevalences were higher in villages using perennial irrigation for 3 yr (32%), for 24 yr (46.2%), and for 95 yr (38.9%).

The New Valley comprises a chain of 5 depressions and oases irrigated by artesian wells in the Western Desert, extending from the northern coast to within 40 km to the west of the Aswan High Dam Lake. The irrigated areas will eventually cover about 84,000 ha with rice as the main crop. Planned migration into the New Valley to increase agricultural production resulted in a population of 91,000 persons in 1975. Only *S. haematobium* was present in 1975 although *Biomphalaria* shells were also found (Abou el-Hassan 1975).

Sudan. The Gezira scheme, with its Manaqil and Rahad extensions, is one of the largest irrigation schemes in the world—more than 840,000 ha. Although rice is not among the major crops, the experience in schistosomiasis control is noteworthy (Fenwick et al 1982). The Blue Nile Health Project has reduced schistosomiasis with chemotherapy, mollusciciding, environmental management, sanitation, water supply, and health education.

Somalia. Only urinary schistosomiasis is present in Somalia. In the older sugarcane irrigation projects the prevalence was 76% at Genale and 58.7% at Giohar. In the newly developed areas, the prevalence was 27.2% at Balad and 58.1% at Afgoi (Arfaa 1975).

Ethiopia. In the Awash Valley, 58,000 ha were irrigated in 1976 and expansion is continuing (Kloos 1985). The prevalence of *S. mansoni* among the population of 150,000 was not high and probably was most important in the Upper Valley. The importance of migrant populations in spreading schistosomiasis has been emphasized.

African Region

Irrigated rice is probably growing at a faster rate in Africa than anywhere else in the world. The examples cited below do not include all endemic countries where rice irrigation is among the development priorities.

Mauritania. Irrigation for rice production in Mauritania, including the plains of Rosso, Boghé and Kaédi, began after the construction of a series of dams (Jobin et al 1976). Although the endemic areas of *S. haematobium* are generally recognized, control has been limited. Sow (1978) noted that although only urinary schistosomiasis is endemic, *Biomphalaria pfeifferi* is present in Atar and Rosso, and Mauritanian workers returning from Gabon were found infected with *S. mansoni.*

Sierra Leone. Over the past 25 yr, agriculture in Sierra Leone has become increasingly oriented toward swamp rice, which is more productive than the traditionally grown upland rice (White et al 1982). The construction of a rice swamp of the type in Sierra Leone involves the complete removal of vegetation from an inland valley swamp and its replacement by an ordered series of fields arranged around a central drainage channel. A dam is constructed at the head of the swamp and water re-enters the control channel through the fields. Ponds are constructed at intervals in the central canal. When these are accessible from a road or are close to a village, they often become domestic-water contact sites for washing and bathing.

The Integrated Agricultural Development Project of the eastern region of Sierra Leone was financed by the World Bank and is administered by the Ministry of Agriculture and Natural Resources. In 1981, 5,000 ha of rice swamps associated with more than 800 villages had been developed.

In 74 villages surveyed with a total population of approximately 25,000 persons, the prevalence of *S. mansoni* infection was 2.5% (4,986 persons examined) and the prevalence of *S. haematobium* infection was 8.2% (6,889 persons examined). The prevalence of schistosomiasis was low despite a high level of water contact, movements of migrants from other endemic areas including Guinea and Liberia, and the proximity to highly endemic areas elsewhere in Sierra Leone. The low prevalence was attributed to the lack of suitable snail habitats and limited populations of snail intermediate hosts. The conductivity of the water in this area was comparable with the lowest values in freshwaters in Africa. *Bulinus globosus, B. forskalii,* and *Biomphalaria pfefferi* were found.

The rice swamp represents a generally distributed habitat. Canal maintenance reduced the vegetation necessary for snail habitats. When natural vegetation was removed to create rice swamp, peak surface water temperature and that of shallow fields exceeded 40 °C. Control of schistosomiasis in this area would be oriented toward identifying infected persons and treating them through the rural health services.

Liberia. Swamp rice farming is playing an increasingly important role in Liberia. The association of schistosomiasis and swamp rice farming varies between these countries. The prevalences of both intestinal and urinary schistosomiasis in a village in Bong county, Liberia, where swamp rice cultivation had begun 6 yr earlier, were significantly higher than in a village where it had not been initiated (Kazura et al 1985). No association was found in Sierra Leone.

A pilot control program using large-scale treatment with metrifonate for *S. haematobium* infection and praziquantel for mixed *S. mansoni* and *S. haematobium* infections, combined with focal application of molluscicides, was undertaken in Bong county (Saladin et al 1983). *S. haematobium* prevalence in 1 village was 43.5% before treatment. Eighteen months after treatment of all infected persons with a single full course of metrifonate, the prevalence was 37.3%, with a significant reduction in egg count. Within 28 mo, however, both prevalence and intensity of infection had returned to pretreatment levels, indicating that annual treatment would be appropriate. Another village near the streams feeding a rice swamp had mixed infections. *S. mansoni* prevalence was 47.6% and *S. haematobium* prevalence was 20.8% before treatment with praziquantel. Eighteen months after treatment, *S. mansoni* prevalence was 25.3% and *S. haematobium* was 4.6%. After 28 mo, the prevalence of *S. haematobium* remained low; however, the prevalence of *S. mansoni* (46.9%) was similar to the pretreatment prevalence (47.6%).

This study emphasizes the wide epidemiological differences in the same geographical area. The ecological and sociocultural factors that influence transmission may vary greatly within short distances.

Niger. Rice cultivation is concentrated and increasing north and south of Niamey along the Niger River. Since 1955, about 10,000 ha have been irrigated and 13,000 additional hectares are projected. *S. haematobium* is highly endemic including villages where all children 5-14 yr old are infected (Bretagne et al 1985).

Cameroon. Rice farming is the major economic activity in northern Cameroon. It was introduced on a small scale in 1950 and in 1971, the Yagoua Society for Expansion and Modernization of Rice Cultivation (SEMRY) was founded. Dams and dikedam on the Logone River and its tributaries brought large areas under irrigation. For example, a 27-km dikedam between Pouss and Guirvidig formed a reservoir covering 34,000 ha at high water level and 14,000 ha at low water. SEMRY I (Yagoua) irrigated 5,300 ha (Wibaux-Charlois 1982, Yelnik et al 1982) and SEMRY II (Maga) has irrigated 7,000 ha of 55,000 ha (Audibert et al 1983) through a system of canals and drainage into the natural swamps. These developments permit two harvests per year.

The population of SEMRY I is about 20,000 and that of SEMRY II about 70,000. At the site of SEMRY II, 7,000 persons were displaced by the reservoir lake. Schistosomiasis in this area is not solely an occupational disease. The risk of transmission is compounded by the proximity of human habitation to the irrigation system, which increases the level of water contact. Within 4 villages in this area, the prevalence ranged from 20.1 to 62.4%. This study (Yelnik et al 1982) showed that there was positive correlation between residence in proximity to the ricefields and the prevalence of urinary schistosomiasis. The prevalence of schistosomiasis was higher in villages without community wells. The irrigated ricefields themselves are not the primary transmission sites (Wibaux-Charlois 1982). The epidemiologically important transmission sites are the secondary and tertiary irrigation canals and drainage canals, particularly those that are poorly maintained and overgrown. More recent irrigation systems have lower snail populations than older systems..

In southwest Cameroon, where the major agricultural activity is coffee growing, the Society of Development of Rice Cultivation in the Mbos plain or SODERIM began in Santchou District in 1973 (Blancheteau and Picot 1983). The rice project covered 18,000 ha with an estimated population of about 20,000 persons in 1988. Urinary schistosomiasis in this area was limited almost entirely to the 10-14 yr age group. The reasons for this unusual epidemiological observation are not known.

United Republic of Tanzania. In northern Tanzania, the Tanganyika Planting Company was established in 1936 and covered 3,600 ha by the 1970s. Schistosomiasis control and its costs were evaluated between 1968 and 1970 (Fenwick 1972, Fenwick and Jorgensen 1972). The prevalence of *S. mansoni* infections among the field workers was reduced from 59% to 31% by the combination of treatment of infected persons and snail control.

Madagascar. The first large-scale control program using an oral antischistosomal drug combined with chemical mollusciciding was undertaken in the rice irrigation scheme in Bas-Mangoky in southwest Madagascar (Degrkmont et al 1972). The area under cultivation was foreseen to reach 40,000 ha. *S. haematobium* transmitted by *Bulinus obtusispira* is endemic in this area.

Swaziland. Urinary schistosomiasis is widespread in Swaziland. The intestinal form was first reported on irrigated estates in the lowveld in 1952 (Logan 1983). Later reports indicated that *S. mansoni* was found in other areas of the country, but the highest prevalences were still in the irrigated areas of the midveld and lowveld.

Within the 42,000 ha of the Commonwealth Development Corporation irrigated estates, rice was a major crop up until 1977-78. Irrigation water reaches these estates through a 68-km unlined canal from the Komati River and is supplemented at low water levels by the Sand River Dam Reservoir. There are three types of concrete lined canals within the estates: ridge canals, which run down the slope of the land and are fast flowing; contour canals, which flow more slowly; and step canals which are filled only when a field is being irrigated. Strikingly, in the rice irrigated areas all canals were *unlined* contour types. Night storage reservoirs are common throughout the system.

In the most recent survey of schistosomiasis in three estates (Logan 1983) the prevalence of *S. haematobium* (range 23.3-29.2%) and *S. mansoni* (range 33.3-59.9%) among field workers was generally higher than among 6- to 8-yr old schoolchildren from the same estates (*S. haematobium* 6.4-37.9% and *S. mansoni* 14.7-41.4%). Dense populations of snail intermediate hosts of both *S. haematobium* and *S. mansoni* were found at the Sand River Dam (where human-water contact was limited), throughout the unlined canal system, and in many lined contour canals. In the night storage reservoirs, snail populations were low or absent. Snails were also found in the field drains but not in the fast flowing main drain.

The prevalence and intensity of infection were lowest in the estates with good sanitation and water supply. This observation confirms the importance of a basic infrastructure to promote schistosomiasis control.

Southeast Asia and Western Pacific Region

Schistosomiasis in the Western Pacific Region is due to *S. japonicum* infection and is closely associated with rice cultivation.

Japan. No new cases of human schistosomiasis have been reported in Japan since 1978 (Hunter and Yokogawa 1984). Before that, five major rice-growing areas—Kofu basin, Tone River basin, Numazu, Fukuyama, and Kurume/Tosu—were all endemic. A long-range program for improved irrigation management with mollusciciding and treatment of infected persons began in 1947.

Philippines. Most of the 150 endemic municipalities in 22 provinces are irrigated rice-growing areas (Santos 1984). The original habitats of *Oncomelania* *quadrasi* were the floodplain forests and swamps. Because this land is desirable for growing lowland rice, the forests are being gradually destroyed and the original habitats persist only in Mindanao. In contrast to Leyte, it was uncommon to find *O. quadrasi* in ricefields in Mindanao, the difference being attributed to the rice cultivation practices in Leyte (Pesigan et al 1958). In Mindanao, repeated plowing and weeding during the growing season disturbed the snail habitats. In Bukidnon Province, snails disappeared after 4-7 yr of consecutive rice farming. Although snails were not found in the fields themselves, the draining canals and seepage ditches were heavily populated.

The populations in the rice-growing areas are at high risk of *S. japonicum* infection. All of the population-based epidemiological studies in the rice-growing areas of Barrio San Antonio, Samar (Lewert et al 1979), Santa Rosa, Leyte (Domingo et al 1980, Olveda et al 1983), and Irosin, Sorsogon (WHO 1980), indicated that enlargement of the liver and spleen correlated with the presence, but not with the intensity, of infection. The highest prevalence was found in the 10-19 yr age group, but it was also high in some older age groups.

Control of schistosomiasis is a high priority for the Department of Health, with support from the national irrigation programs. Control is coordinated through the provincial health services with technical support from the Schistosomiasis Research and Control Service (Santos, 1984). The prevalence of schistosomiasis is gradually decreasing in areas where large-scale chemotherapy programs are under way.

China. When Faust and Meleney wrote their classic monograph on schistosomiasis due to *S. japonicum* in 1924, the disease was limited almost entirely to rice-growing areas and was most closely associated with that occupation. The prevalence of schistosomiasis was much higher along the Yangtze River basin and in the three large lakes south of the river, where one or two rice crops were obtained each year, than in areas south of Fuzhou where three crops were often obtained. Furthermore, the snail density in rice seedling beds was high at transplanting. Today, however, the ricefields themselves are not foci of transmission due to repetitive cultivation and weeding which disturb potential snail habitats.

The distribution of schistosomiasis in China is highly aggregated, e.g., prevalence, intensity of infection, and morbidity vary greatly between localities, even those that are short distances apart. The *Oncomelania* habitats are related to snail type, vegetation, temperature, and rainfall rather than to rice cropping cycles. The traditional use of human feces as fertilizer remains unchanged today and is the primary source of contamination.

Schistosomiasis due to *S. japonicum* continues to be a major public health problem in the marshlands, swamp, and lake regions of the Yangtze River basin, but the prevalence of schistosomiasis has been greatly reduced from previous levels (Mao 1986). In these areas, domestic animals are also infected and effective control requires coordinated treatment of animals and humans as well as snail control.

Indonesia. The limited foci of schistosomiasis in Central Sulawesi are associated with rice irrigation in the Napu Valley (Carney et al 1975). In Lindu Valley, snail colonies are found in abandoned ricefields and drainage ditches as well as in the snail streams and virgin forests (Sudomo 1984). Control is being achieved by large-scale chemotherapy with praziquantel.

Conclusion

Control of schistosomiasis in irrigated rice will be, as has been in the past, a major challenge in the future. The wide range of epidemiological, ecological, and sociocultural differences between endemic countries will require specific plans of action to promote control within each endemic country. The inclusion of medical services, water supply, and sanitation for the human communities related to the irrigation scheme are essential infrastructure to assure effective control with the available diagnostic techniques and antischistosomal drugs. Once schistosomiasis is endemic in a rice irrigation scheme, its control is a long-term and expensive, but feasible, operation. Schistosomiasis prevention, systematic diagnosis, and treatment, combined with appropriate snail control and environmental management, are relatively cost effective.

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Author's address: N. R. Bergquist. UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases. 1211 Geneva 27. Switzerland; Chen Ming-gang and K.E. Mott. World Health Organization, 121I Geneva 27, Switzerland.

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Strategies for control of Japanese encephalitis in rice production systems in developing countries

Y. Wada

Measures to protect humans and pigs and to control mosquitoes to prevent transmission of Japanese encephalitis are discussed. Generally, the first measure to consider is vaccinating humans, because vaccination is well established. The vaccination of pigs, which are the most important amplifying animal of Japanese encephalitis (JE) virus, is of little practical value. Separating pigs from ricefields is the surest way to reduce pig-mosquito contact. Most measures to control vector mosquitoes are of no operational value, at least in the present situation, and need further study. Developing new rice varieties with high yield and reduced water and fertilizer requirements seems a promising method to reduce mosquito density. Another approach is to reduce the number of mosquitoes engorged with pig blood, which may include mosquitoes just infected with JE virus. Modification of pigsty structures, treatment of pigsty walls with residual insecticides, and light traps could be successful. Further studies of these kinds of measures are recommended.

Japanese encephalitis is a serious human disease with high mortality in the Far East, and South and Southeast Asia. It is transmitted by mosquitoes, of which *Culex tritaeniorhynchus* is the most important, Because ricefields are the main breeding sites of *C. tritaeniorhynchus,* Japanese encephalitis is closely associated with rice production.

Japanese encephalitis is principally a disease of birds in marshy areas in Southeast Asia. However, in the epidemiology of Japanese encephalitis, pigs, at least at present, play a far more important role than birds as the amplifying animal of the causative virus. Japanese encephalitis (JE) virus is transmitted to humans through the bite of infected vector mosquitoes by feeding on viremic animals, but the virus does not appear in the blood of humans. Therefore, humans are a dead-end host of JE virus in a sense that they cannot be a source of new infection.

The JE virus transmitted by mosquitoes is not circulated in the human population, but in amplifying animals, of which pigs are the most important. The epidemic of Japanese encephalitis in humans depends largely on the epizootic in pigs. It is clear that measures to protect humans and pigs, and to reduce mosquito populations can be considered for the control of Japanese encephalitis.

Measures to protect humans

The vaccination of humans with inactivated Japanese encephalitis vaccine effectively reduces the incidence of Japanese encephalitis. Purified vaccine from infected mouse brain is produced in Japan, Korea, and Taiwan, and cell culture vaccine from infected hamster kidney cells is produced in China (Oya 1986).

Hsu et al (1971) reported a large-scale field trial with purified vaccine from mouse brain in 400,000 children in Taiwan. Protection rate was calculated as 80%. Field studies on inactivated vaccine from cell culture were carried out on more than 70,000 children in Guangdong Province, China, with a protection rate of about 95% (Huang 1982).

Ishii (1986) reported the influence of human vaccination in Japan. The administration of purified JE vaccine to humans started in 1954. The vaccine has been given to children 3-15 yr old. The annual incidence of Japanese encephalitis cases decreased rapidly after the end of 1960s when the maximum amount of vaccine was produced. Although the density of vector mosquitoes became low during the period, it is certain that human vaccination played an important role in reducing the number of human cases. Additional evidence of the effectiveness is that the incidence rate by age group decreased more markedly in vaccinated children than in elderly persons, when the rates in 1950 were compared to the recent 10 yr.

Human vaccination has no impact on the transmission cycle of JE virus in the field. Nevertheless, it should be considered first in the control of Japanese encephalitis due to its effectiveness in reducing the number of human cases.

Other measures to humans are related to the reduction of human-mosquito contact. Screening houses and using mosquito nets reduce human-mosquito contact as well as siting human dwellings far from ricefields where *C. tritaeniorhynchus* breeds. These measures effectively reduce the incidence of Japanese encephalitis, but they are not easy to put into practice.

C. tritaeniorhynchus is a zoophilic mosquito that likes to feed on cows and pigs. Although cows are not involved in the transmission cycle of Japanese encephalitis because of the low virus titer in their blood, they affect Japanese encephalitis epidemics in opposing ways. On one hand, cows lead to an *increase* in the density of *C. tritaeniorhynchus* by supplying a blood source for reproduction. At the same time, they *decrease* the transmission efficiency of JE virus in the pig-mosquito cycle (Carey et al 1968). Therefore, it is difficult to say whether cows in rice production systems contribute to an increase or decrease in the incidence of Japanese encephalitis. However, if a large number of cows are kept between dwellings and ricefields, that might decrease the chances for humans to be bitten by *C. tritaeniorhynchus* and become infected with JE virus. Studies are required before this approach can be practically applied in Japanese encephalitis control.

Measures to protect pigs

Scherer et al (1959) indicated that pigs are the main amplifying animal of JE virus in Japan, and Oya (1967) and others confirmed that view. Therefore, it is argued that immunizing pigs may reduce the size of Japanese encephalitis epidemics in humans by reducing the rate of mosquito infection. Oya (1967) attempted to confirm this hypothesis in the field. He selected an isolated village with 56 pigs as a vaccination area and another village about 3 km away as the control. Pigs, rabbits, bovines, and goats were all immunized in the vaccinated village. Females of *C. tritaeniorhynchus* in both villages were examined for infection with JE virus throughout the epidemic season. There was a 2-wk delay in the appearance of infected mosquitoes in the vaccinated area, but there was no difference in the infection rate of mosquitoes.

Later, Maeda (1968), Wada et al (1969), and Baily and Gould (1975) demonstrated that this vector mosquito has the ability to disperse several kilometers per day. These findings indicated that a sufficiently wide area should be selected for field evaluation of pig vaccination.

Iki Island in Kyushu, Japan, was selected by Takahashi et al (1968) for similar studies. Iki is 40 km off the mainland and has an area of 138 km^2. All domesticated pigs on the island—2,166 in 1967 and 1,740 in 1968—were immunized with live attenuated vaccine. Much lower infection rates were observed in mosquitoes from Iki Island than in those from the mainland. Furthermore, the number of human Japanese encephalitis cases dropped from 18 in 1966 to only 1 in 1967 and 1 in 1968. It is not clear whether this decrease in the number of Japanese encephalitis cases could be attributed to the pig immunization alone, since a similar decrease was observed on the mainland.

Pig immunization was also carried out in Kyoto City from 1968 to 1970 (Tsuchiya et al 1970). Live vaccine was administered to every pig approximately 1 mo before the expected starting time of the epidemic. A significant decrease in the infection rate of mosquitoes, as well as a delay in the onset of mosquito infection, was observed in the vaccinated area in 1968 and 1969, but not in 1970. The lack of difference in 1970 was explained by the fact that the epidemic started much later that year and immunized pigs were sold off from more than 50% of the pigsties and replaced by unprotected pigs.

Recently, in Kumamoto City, which had the highest recorded Japanese encephalitis morbidity during the last 8 yr in Japan, pigs were immunized to control Japanese encephalitis epidemic. About 25,000 pigs in the area surrounding the city were immunized with live vaccine in 1985. The number of human cases dropped from 9 the previous year to 1 in 1985.

Pig immunization is theoretically a promising approach to Japanese encephalitis control (Wada 1975b), although many practical problems remain. One of the problems is timing the pig immunization. Pigs must be vaccinated after the maternal antibody disappears from the pig's body but before Japanese encephalitis epizootic starts. In temperate areas such as Korea, Japan, and northern China, the epizootic appears at a particular time of year (Kim 1986, Ishii 1986, Wang 1986); pig immunization could be timed to coincide with the appearance. However, Japanese encephalitis infection occurs throughout the year in the tropics (Simpson et al 1970, Sangkawibha et al 1986); pig vaccination there may be of little practical value.

Besides pig immunization, siting pigsties far from ricefields is suggested. Hundreds of human cases of Japanese encephalitis were recorded annually in Japan in the 1960s, but the number decreased to tens or less in the 1970s. During that decade, there was a clear relation between the number of human cases and the density of vector mosquitoes (Wada 1975a, Maeda et al 1978).

There was no appreciable increase in the number of human cases in the 1980s despite the increase in vector mosquitoes. That discrepancy between the number of human cases and the density of vector mosquitoes seems to be due to many pigsties being moved far from ricefields during the 1970s, thus reducing pig-mosquito contacts.

Measures to control mosquitoes

Chemical control

C. tritaeniorhynchus is the most important vector of Japanese encephalitis and its control is of great concern to medical entomologists (Wada 1974). Vector control strategies in rice production systems were reviewed by Mogi (1984). Various insecticides were tested in the laboratory and in the field for the control of this mosquito. The application of insecticides to ricefields is effective in controlling the *C. tritaeniorhynchus* population, but usually for only 1 or 2 wk (Asahina et al 1963, Ogata and Nakayama 1963). Therefore, to control vector mosquitoes by larviciding, several applications a year are necessary. Because of the vast area of ricefields, the use of larvicides to control Japanese encephalitis will be expensive and probably of no operational value in usual circumstances. Moreover, the chemical control of *C. tritaeniorhynchus* by using organophosphorus and carbamate insecticides has become ineffective in recent years because of the development of insecticide resistance, at least in Japan.

Aerial spray of insecticides against adult *C. tritaeniorhynchus* seems impractical for the same reason, since adults rest in large areas of ricefields and in nearby grassylands.

Residual spraying of insecticides does not control *C. tritaeniorhynchus* (Nishigaki 1970). In Nagasaki Prefecture, Japan, he residual sprayed malathion or fenthion on the inside walls of all animal sheds and houses. Contrary to results obtained with *C. pipiens pallens, C. tritaeniorhynchus* populations were reduced slightly for only a few days after the residual spray. This is probably due to the exophilic nature of *C. tritaeniorhynchus.*

Although the effect of insecticidal spraying against vector mosquitoes is rather discouraging from a practical viewpoint, populations of *C. tritaeniorhynchus* are reduced by various agricultural insecticides used to control rice pests (Kamimura and Katori 1969, Self et al 1973). Maeda and Matsuyama (1967), Moriya et al (1969), and Buie and Ito (1974) reported that *C. tritaeniorhynchus* populations in the Kyoto, Kanagawa, and Osaka areas in Japan were susceptible to organophosphorus insecticides. It seems that agricultural insecticides against rice pests were also effective against mosquitoes until the mid-1970s.

However, Kamimura and Maruyama (1983) first observed that insecticides sprayed in ricefields did not have any impact on *C. tritaeniorhynchus* in the Toyama area in Japan. In laboratory studies of the susceptibility of *C. tritaeniorhynchus* to insecticides they found the Toyama colony highly resistant to malathion and fenitrothion, but still rather susceptible to DDT.

Following the report by Kamimura and Maruyama (1983), the National Institute of Health, Tokyo, started studies in 1984 on the susceptibility of *C. tritaeniorhynchus* larvae from 14 sites in Japan to organophosphorus, carbamate, and pyrethroid insecticides (Yasutomi and Takahashi 1987). They found surprisingly high resistance to the organophosphorus malathion and fenitrothion, and the carbamate propoxur (LC_{50} values higher than 10 ppm), but susceptibility to the pyrethroid permethrin. The extremely high resistance of *C. tritaeniorhynchus* to organophosphorus and carbamate insecticides all over Japan appears to have been caused by the use of agricultural pesticides since these insecticides had not been used against ricefield mosquitoes. This implies that the ineffectiveness of agricultural pesticides against *C. tritaeniorhynchus* is, at least partly, the reason for increased density of this mosquito in Japan in recent years. It is possible that ricefield mosquitoes develop insecticide resistance wherever agricultural insecticides are used.

Biological Control

It is evident that some natural enemies play an important role in reducing the number of *C. tritaeniorhynchus,* at least under certain circumstances (Mogi 1978; Mogi et al 1980a,b; Wada 1974). For example, immediately after hatching about 3,300 first-instar larvae were placed in each of 3 experimental plots. The number of adults emerging 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. Other evidence indicated that spiders are also important in reducing the number of adult mosquitoes. Mass-rearing natural enemies of target mosquitoes is apparently uneconomical.

Some fishes are significant natural enemies of mosquito larvae. But the introduction of a new natural enemy to uninhabited areas is successful only under special circumstances. *Gambusia,* a predator of mosquitoes, invaded parts of Japan and drove a native fish, with the same ecological niche, almost completely out of the ricefields. *Gambusia,* therefore, added little to the role of natural enemies in mosquito control. This underscores the importance of careful studies before introducing any exotic natural enemies.

Although introducing natural enemies is rather discouraging, their natural populations should be protected. Agricultural insecticides sprayed in ricefields affect not only *C. tritaeniorhynchus* but also its natural enemies. The decrease of *C. tritaeniorhynchus* after 1970 is perhaps due, in part, to the increase of its natural enemies by the switch from chlorinated hydrocarbons to carbamates (Mogi 1978, Wada 1974). Agricultural chemicals that adversely affect natural enemies of rice pest and mosquitoes should not be used.

Cultural control

C. tritaeniorhynchus populations in ricefields are greatly influenced by rice planting practice. Mosquito populations increase significantly after transplanting, when the area of irrigation increases greatly and the water becomes suitable for mosquito breeding as a result of fertilizing the rice plants. This was observed in Sarawak by Hill (1970) and in Japan by many investigators. It is desirable to change the agricultural practices, including water management and adjusting planting time (Mogi 1984), to reduce mosquito density.

However, changes in agricultural practices must be considered in relation to rice production; therefore this approach has its limitation. Particularly interesting is the development of new rice varieties that need less water and less fertilizer. Such varieties will certainly reduce the density of *C. tritaeniorhynchus.*

An entomological approach to Japanese encephalitis control is the use of the light trap (Mogi 1978, 1984; Wada 1974). Light traps at pigsties attract and kill many *C. tritaeniorhynchus,* without attracting their natural enemies. The light trap could also contribute to lowering the transmission of JE virus by killing many engorged females, including those recently infected by having fed on viremic pigs. The light trap should be evaluated in the field to determine whether it could be used for control of Japanese encephalitis. Mosquito-proof pigsties would also decrease the transmission of JE virus.

Conclusions

Generally speaking, the first step in Japanese encephalitis control is vaccination of humans. The effectiveness of vaccination is well established, effective vaccine is available, and the acquired immunity usually lasts for a considerable period.

The vaccination of pigs is another method to control Japanese encephalitis. Pigs must be vaccinated after the maternal antibody disappears from the body of the pigs, but before the Japanese encephalitis epidemic starts. In tropical countries, pig vaccination may be impractical, since Japanese encephalitis infection continues throughout the year. Pigs should be removed from near ricefields to reduce pig-mosquito contact.

Most measures to control mosquitoes need further study or are impractical at present. However, they should be applied whenever possible. Developing new varieties of high-yielding rice with reduced water and fertilizer requirements seems promising. Such varieties would help reduce the density of mosquitoes by providing fewer breeding sites and less nourishment for larval development.

Another approach to control of Japanese encephalitis is decreasing the number of mosquitoes engorged with pig blood, including those infected with JE virus, to reduce the transmission of the virus. That may be achieved by modifying the structure of pigsties and using light traps at pigsties. Studies along this line should be strengthened.

Each measure aimed at humans, pigs, or mosquitoes will be effective to various degrees, but what is applied should be decided through careful cost-benefit analyses. Method must be appropriate to the situation of each country. To decide the applicable strategies for Japanese encephalitis control, extensive basic studies are indispensable.

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Notes

Acknowledgment: Work performed at Department of Medical Entomology, National Institute of Health, 10-35, 2 Chome, Kamiosaki, Shinangawa-Ku, Tokyo, Japan.

Author's present address: Department of Medical Entomology, Institute of Tropical Medicine, Nagasaki University, Sakamoto–machi 12-4, Nagasaki 852,. Japan.

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Strategies for vector-borne disease control in rice production systems in developing countries: arboviruses other than Japanese encephalitis

C. J. LEAKE

More than 40 viruses have been isolated in studies on riceland agroecosystems but only a few are considered public health problems. Important alphaviruses are O'nyong-nyong from Africa and the equine encephalitis viruses from the Americas. Principal flaviviruses are West Nile virus distributed from the Mediterranean to South Asia, St. Louis encephalitis from the Americas, and Murray Valley encephalitis from the Indo-Australian archipelago. Several bunyaviruses of increasing significance in the United States are anticipated to be much more widely distributed. These viruses are probably maintained in zoonotic cycles of continuous or possibly transovarial transmission. Principal culicine mosquito vectors are primarily zoophilic with human transmission correlating with peaks in vector density associated with temperature, water availability, and agricultural practice. Clinical care is only supportive; there are no commercially available vaccines. Consideration of the bionomics of these vectors in relation to available integrated control strategies suggests that some transmission reduction might be achieved. Permanent reduction in vector populations would be too costly for developing countries and substantial temporary reduction may be warranted only under epidemic conditions.

More than 40 viruses have been isolated from humans, animals, or mosquitoes broadly associated with ricefield ecosystems (ASTMH 1985). The status of many of them as true arboviruses is uncertain or untested, and few have been associated with serious human or veterinary disease.

Nevertheless, a number of viruses pose significant problems because of the seriousness of disease symptoms, or have epidemic potential because of the widespread distribution of proven or potential vectors and maintenance hosts. The ease with which arboviruses can spread to new areas, become established (Johnson and Chanas 1981), and cause large-scale problems has been emphasized in the last few years by major outbreaks of the flavivirus Japanese encephalitis in northern India (Rodriguez 1984) and Nepal (unpubl. data), epidemics of the bunyavirus Rift Valley fever in Egypt (WHO 1977, 1978), and the spread of the alphavirus Ross River through the Pacific Islands (Marshall and Miles 1984), all showing new virus-vector associations. These examples and the emergence of new agents such as the flavivirus Rocio (Lopes 1981) in South America reinforce the gap between our expanding knowledge of the epidemiology of arboviruses and their vectors and the total lack of effective control measures in most areas (Reeves 1982).

Viruses of principal public health concern

The viruses of principal concern produce a spectrum of symptoms ranging from febrile illnesses with fever and rash to acute encephalitis.

Alphaviruses

O'nyong-nyong (ONN) virus was first isolated during a massive epidemic in East Africa from 1959 to 1962 involving more than 2 million people (Gillett, pers. comm.); although typically nonfatal, the virus causes fever with rash and crippling joint pains from which recovery can be prolonged. ONN virus spread from northwest Uganda into Kenya, Tanzania, and Malawi, in some areas affecting up to 70% of the population. Many isolates have been obtained from *Anopheles funestus* and *Anopheles gambiae* mosquitoes, well-known malaria vectors, which breed largely in marshes and sunlit pools (Gillett, pers. comm.). Rice cultivation has been encouraged in many parts of the region; increased breeding of these mosquito species and high virus activity have been documented in the Kisumu rice irrigation project in Kenya (Simpson 1975).

The related alphaviruses Sindbis and Getah are widely distributed; Sindbis has been reported from the Mediterranean to Australia and Getah from Southeast Asia and Australia. Sindbis virus causes fever with rash and although encephalitis has been seen in horses infected with Getah virus, human illness has not been described. Both viruses have been isolated from several species of *Culex vishnui* group mosquitoes (ASTMH 1985).

A recent human antibody survey (Kanamitsu et al 1979) in the Indo-Australian archipelago indicated relatively low-level human alphavirus activity in the area conducive to epidemic spread of these viruses. In addition to Ross River virus (Marshall and Miles 1984), the equine encephalitis viruses are related alphaviruses, which are principally maintained in animal-mosquito cycles. Their severe clinical pattern in humans and their isolation from numerous mosquito species over large geographic ranges emphasize their epidemic potential. Fortunately, these viruses are distributed in the Americas although eastern equine encephalitis virus has apparently been isolated in Thailand and the Philippines (ASTMH 1985). Overt human disease caused by eastern equine encephalitis virus has not been frequently reported, although human antibody is widespread in Central and South America. Numerous mosquito isolates of eastern equine encephalitis virus have been made and many mosquito species are susceptible in the laboratory. Hundreds of cases of western equine encephalitis virus have been described. The virus is distributed across much of North America with extension into many areas of Central and South America. Western equine encephalitis virus has been isolated from five genera of mosquitoes, but the principal human vector is *Culex tarsalis,* which breeds under a variety of conditions and is found, for example, in large numbers in California ricefields (Markos 1951). Tens of thousands of human cases of Venezuelan equine encephalitis virus and large-scale epizootics in horses have been described throughout the tropical Americas (ASTMH 1985). Epidemic strains of the virus have been isolated from 26 species of mosquitoes including *Culex tarsalis.*

Flaviviruses

West Nile virus is widely distributed from France and Portugal in the west through much of Africa, India, and the USSR, with suspected extension into Southeast Asia (ASTMH 1985). Typical symptoms are fever with rash, although central nervous system involvement has been described. Isolations have been made from numerous species of ricefield-associated mosquitoes such as *Culex vishnui* in India. *Culex tritaeniorhynchus* has been shown to be an excellent experimental vector in Pakistan (Hayes et al 1980). West Nile virus is a good example of a virus that was introduced and subsequently maintained in a zoonotic cycle in the Camargue region of France, where the rice area greatly increased between 1942 and 1964. In 1963, febrile human illness was recognized and substantial West Nile serological activity was detected in horses, rodents, migratory birds, and humans. The virus was isolated from *Culex modestus* mosquitoes (Hannoun et al 1964).

Saint Louis encephalitis virus is the most important encephalitic flavivirus from the New World, with several thousand cases having been reported in epidemics from the U.S. The virus is distributed as far south as Brazil and Argentina, but epidemics have not been described outside the U.S. and Canada. The virus has been isolated from numerous species of mosquitoes; the principal vector is considered *Culex tarsalis* (APHA 1980).

Murray Valley encephalitis is an endemic flavivirus in Northern Territory and Queensland, Australia, and in Papua New Guinea, with several hundred clinical cases of Murray Valley encephalitis having been recorded. Epidemic activity has been concentrated in the northern states of Australia (Stanley 1982). Antibody to Murray Valley encephalitis virus is widespread in the Indo-Australian archipelago at low frequency (Kanamitsu et al 1979) and is restricted to the lowlands in Papua New Guinea (Alpers 1982). Murray Valley encephalitis virus is associated principally with *Culex annulirostris* and *Culex bitaeniorhynchus* mosquitoes.

Kunjin is a widely distributed flavivirus in the Indo-Australian archipelago (Kanamitsu et al 1979) with antibody incidence in humans, domestic fowl, and cattle. A case of human encephalitis has recently been described in Australia (Muller et al 1986). The main vectors are *Culex annulirostris* and *Culex pseudovishnui.*

Bunyaviruses

The California encephalitis group of bunyaviruses caused many cases of encephalitis in the U.S. and Canada between 1963 and 1981 (Kappus et al 1983). Distribution of many of these viruses extends into South America. Representatives have been described in Europe and it is probable that others will be isolated from other geographic regions. Many of these viruses have been principally associated with *Aedes* mosquitoes, but a wide range of other species are probably involved including *Culex tarsalis.*

Vector bionomics

Reviews (Burke and Leake 1987, Mitchell et al 1980) of the bionomics of *Culex tritaeniorhynchus,* the principal human vector of JE virus and from which Aino, Akabane, Arkonam, Getah, Kaikalur, Sagiyama, Sindbis, Tembusu, and West Nile viruses have all been isolated (ASTMH 1985), and of *Culex tarsalis,* the principal human vector of St. Louis encephalitis and western equine encephalitis and from which Cache Valley, California encephalitis, Flanders, Grey Lodge, Hart Park, Llano Seco, Lokern, Main Drain, Turlock, Umatilla, and Venezuelan equine encephalitis viruses have been isolated, will be used to illustrate that a thorough knowledge of vector bionomics is central to the design of control strategies.

Breeding sites

Vector species are not solely restricted to ricefield breeding sites, which means that large areas must be considered in control procedures. *Culex tritaeniorhynchus* breeds principally in ricefields or in associated irrigation channels, swampy surroundings, and small temporary pools. *Culex tarsalis* breeding is also closely associated with human-made habitats of irrigated agriculture of all types. Ricefields in the Sacramento valley of California produce large numbers of mosquitoes. In both species, egg rafts are laid on the surface of the water 2-3 d after a blood meal. The eggs cannot withstand desiccation.

Biting activity

Culex tritaeniorhynchus are night feeders with a steady biting rate throughout the night (Hill 1970) or with two biting peaks. Feeding begins shortly after sunset but declines between 2200 and 2300 h and then increases after 2400 h before declining sharply again after 0500 h and ceases by 0600 h (Wada et al 1970). Trap bait is a major influencing factor (Scherer et al 1959). *Culex tarsalis* are similarly nocturnal. Timing of personal protection or adult mosquito control will depend on vector activity.

Host preference

Culex tritaeniorhynchus are zoophilic mosquitoes preferring to bite animals rather than humans. In Japan, 95.2% of mosquitoes collected were in traps baited with pigs, 4.6% in similar traps with a ricefield-breeding bird (black crowned night heron), and only 0.2% in human-baited traps (Scherer et al 1959). Blood meal identification studies have also shown *Culex tritaeniorhynchus* to have a marked feeding preference for cows and pigs, a lesser preference for horses, goats, dogs, and chickens, and almost no attraction for humans. Similarly, *Culex tarsalis* is primarily a bird feeder, but an interesting midsummer shift to feeding on mammalian hosts has been noted. Although the reasons for this are unclear, it is very important in the transmission of St. Louis encephalitis and western equine encephalitis to humans (Mitchell et al 1980).

Both *Culex tritaeniorhynchus* and *Culex tarsalis* are exophagic, exophilic mosquitoes feeding and resting outdoors. The resting sites are rather poorly defined, which complicates the use of residual insecticides.

Flight range and dispersal

Culex tritaeniorhynchus and *Culex tarsalis* mosquitoes are strong flyers. *Culex tritaeniorhynchus* showed a mean dispersal of 1.0 km over 7 d in Japan, with a maximum dispersal 1 d after release of 5.1 km, and a maximum recorded dispersal of 8.4 km 3 d after release. Dispersal was random, but studies of the topography of the release site indicated that the mosquitoes avoided flying over hills and flew over a 2-km stretch of water (Wada et al 1969). *Culex tarsalis* in the Sacramento valley dispersed randomly at low wind velocities but directionally with the wind as velocities increased until flight was inhibited by velocities higher than 10 km/h. Captures were made up to 32 km from the release point leading researchers to conclude that *Culex tarsalis* can probably travel 13-16 km in 2 evenings (Bailey et al 1965). Experimental application of aerial ultralow-volume (ULV) application of malathion to control *Culex tarsalis* showed that mosquitoes breeding outside the treated area rapidly infiltrated the sprayed area (Mitchell et al 1970), emphasizing the difficulty of obtaining a permanent reduction in vectors. The distribution and movement of insects over long distances and the potential seasonal introduction of infected insects as a result of weather, the timing of the monsoon, and prevailing winds has been reviewed (Sellers 1980).

Population dynamics

The population dynamics of *Culex tritaeniorhynchus* in relation to climate and to agricultural practices have been thoroughly reviewed (Reisen et al 1976). In Pakistan, Japan, and Korea, with dry and cold maritime climates, *Culex tritaeniorhynchus* apparently overwinters as hibernating adults. In the warmer maritime climates of Okinawa and Taiwan, breeding continues throughout the year with population curves closely following the annual temperature curves. In tropical climates, population patterns closely follow water availability either from rainfall or irrigation. The relation between *Culex tritaeniorhynchus* breeding and agricultural practice in Sarawak has been described in detail (Heathcote 1970). At breeding peak time, before rice planting in October, it was calculated that an average-sized field (320 m^2) would produce up to 30,000 adults daily for 3-5 d. Because cultivation and planting are spread over 6 wk, a large increase in the adult population occurs in the area. Population peaks of *Culex tarsalis* frequently have been associated with epidemics of St. Louis encephalitis and western equine encephalitis (Mitchell et al 1980).

An analysis of age-composition and survival of field populations of *Culex tritaeniorhynchus* demonstrated that large numbers of mosquitoes had to be infected originally (629 in July, daily survival 0.525; 361 in August, daily survival 0.555) for a single mosquito to survive for 10 d, the approximate time required for the mosquito to become infectious (Buei and Ito 1982). In California the majority of hibernating *Culex tarsalis* are nulliparous leading to the conclusion that adult mosquitoes probably do not act as major overwintering reservoirs for western equine encephalitis and St. Louis encephalitis viruses (Reeves 1974).

Virus-vector interaction

The effects of various parameters on the laboratory vector competence of *Culex tritaeniorhynchus* and *Culex tarsalis* have been reviewed (Burke and Leake 1987, Mitchell et al 1980). Temperature has the most significant effect on the extrinsic incubation period of viruses in vectors. Prevailing weather factors are, therefore, major controlling factors in the replication of viruses in mosquitoes, with temperature perhaps having a multiple effect. In addition to affecting the extrinsic incubation period of the virus, high temperature may increase vector populations as a result of greater survival from a shorter larval breeding period, but may adversely affect adult survivorship. Large amounts of rain may flush out mosquito breeding sites, whereas too little rain may restrict population size. In areas with well-developed irrigation schemes, rainfall may be less significant.

Daylength may also be important in that *Culex tritaeniorhynchus* feed more readily during longer days (Eldridge 1963). Higher mosquito infection rates and more rapidly rising virus titres in the salivary gland secretion have been demonstrated in mosquitoes maintained on long-day regimes (Cates and Huang 1969). When mosquitoes were reared, infected, and maintained in a biotron to simulate temperature, humidity, and daylength on daily and seasonal cycles, they had lower concentrations of virus restricted to the posterior midgut in autumn or winter than those infected in summer (Shichijo et al 1972). There appear to have been no studies on field microenvironment, although it must play a critical role in the interaction between virus, vector, and host and is an important area for future study.

Transovarial transmission

Leake (1984) reviewed the significance of transovarial transmission of arboviruses by mosquitoes in relation to epidemiology of arboviruses and control. Transovarial transmission potentially yields infected individuals capable of transmission at their first blood meal. In this situation, field survival of adults would be relatively unimportant. When transovarial transmission is combined with autogeny, viruses theoretically could be maintained without vertebrate hosts. Transovarial transmission has been demonstrated in the laboratory with several flaviviruses such as St. Louis encephalitis, Murray Valley encephalitis, yellow fever, and dengue, but generally there is much less evidence indicating that transovarial transmission of alphaviruses occurs. Several bunyaviruses have been shown to be transmitted transovarially and one, Keystone virus, probably overwinters by this mechanism. Although a number of virus isolations have been made from male mosquitoes, few field data are available and this is an important area for future research (Leake 1984).

Control strategies

Arbovirus transmission can be controlled by a variety of methods. To be appropriate for developing countries, the methods must be economical, acceptable, and readily available. An integrated approach would probably be the most effective strategy.

Surveillance

Surveillance is a fundamental requirement of any control strategy; it is particularly important in the context of the arbovirus diseases. Most are poorly studied and underestimated problems that require local assessment. Teams to assess endemic disease risk and the threat of disease introduction, and to develop and apply new rapid diagnosis techniques, need to be established in many areas. Field epidemiological work backed by laboratory studies is required to incriminate vector species, assess vector bionomics, and modify control procedures to local requirements. The teams would need to have a balance between clinical, virological, entomological, and taxonomic staff with adequate technical support, laboratories, and transportation. Data obtained should be integrated at national and regional levels with the long-term aim of establishing predictive models for epidemic risk.

Personal protection

Vaccination/chemoprophylaxis. Currently there are no commercially available arbovirus vaccines other than those for yellow fever and Japanese encephalitis, although several others are being investigated or are available on a limited basis, i.e., tick-borne encephalitis and Venezuelan equine encephalitis vaccines. Clinical care is mainly supportive as the use of antiviral agents is in its infancy (Galasso 1981).

Repellents. Repellents such as diethyl-m-toluamide (DEET) may be valuable, particularly as vectors such as *Culex tritaeniorhynchus* take their blood meals principally outdoors in the early evening when humans are still active near their homes. DEET-impregnated anklets worn by human subjects sitting outside on chairs have shown 84% reduction in landing rates of *Culex quinquefaciatus* and *Anopheles funestus* mosquitoes, about 65% effectiveness against *Anopheles gambiae* and *Anopheles coustani,* and 50% effectiveness against *Mansonia* species for up to 3 mo after impregnation of the anklets with 2 h use per night. Further evaluation is required, but at a cost of around $0.50/person per yr for the repellent it appears an attractive option (Curtis et al 1987).

Screening. Screening may be feasible where houses are constructed tightly and adequate screen frames can be constructed. This may not be practical in poorer areas but it is desirable. Curtain screens, impregnated with permethrin and draped around the eaves of houses, have been less effective than hoped (Lines et al 1987).

Bed nets. Bed nets or mosquito nets, untreated if in perfect condition or impregnated with permethrin if they are torn, reduce mosquito bites significantly.

Nets of a suitable quality to survive several seasons cost a minimum $4.00 for a family-sized net of approximately 15 m^2 (Self, pers. comm.). Unfortunately, the peak biting rate of mosquito species such as *Culex tritaeniorhynchus* may be well before individuals retire.

Education. The perception of mosquitoes as disease risks needs to be reinforced. Additionally, altered behavior and farming practices should be encouraged. For example, the most likely times and places of human exposure to infectious mosquitoes is outside after dusk and during the predawn biting peaks. Outside activities, particularly those of children, should be discouraged during those times. The increasing ownership of television sets even by persons in remote areas may decrease exposure (Gahlinger et al 1986) provided the sets are used indoors. Inasmuch as the principal vectors are mainly zoophilic, domestic animals could be sited well away from houses on a communal farm area, but in the absence of animals, mosquitoes may bite humans. An alternative strategy would be to site animal sheds between housing and mosquito breeding areas to attract the mosquitoes as they fly into villages for feeding.

Vector control

Adult mosquitoes. In general, adult vector control depends on insecticides. DDT, malathion, and HCH are the main insecticides used for residual house spraying (WHO 1983). Residual spraying of houses would not be appropriate against the many exophilic and exophagic virus vectors, but would be useful for resting areas such as pigsties and cattle sheds. Outdoor space spraying with malathion, fenitrothion, and pyrethrins may be used (WHO 1983), but the strong flight performance of arbovirus vectors such as *Culex tritaeniorhynchus* would require repeated treatment of large areas making permanent control prohibitively expensive. Nevertheless, where an arbovirus epidemic is clearly defined, emergency spraying might be valuable. Aerial ULV application of fenitrothion reduced the number of adult *Culex tritaeniorhynchus* by 80% for the first 96 h after application, but malathion had little effect (Self et al 1973). Vector resistance to insecticides is becoming an increasing problem, probably aggravated by the widespread use of agricultural pesticides. In many areas *Culex tritaeniorhynchus* show a marked larval resistance to organophosphate compounds, and resistance to carbamates has been detected in Japan and Sri Lanka. This is not currently an operational constraint for control of adult mosquitoes (Hemingway, pers. comm.).

Genetic control of mosquitoes. Sterile male release is being used on a large scale against agricultural pests. Much research has been done and several field trials have been attempted using genetic control methods against mosquitoes. Apart from a continuing study with *C. tarsalis* in California, all such work has been discontinued (Curtis 1985) and none have been included in integrated control programs (WHO 1983).

Control of mosquito larvae. Widespread chemical larviciding of ricefields is impractical for the same reasons as adult insecticide use. A number of alternatives such as *Bacillus thuringiensis* serotype H-14 exist as well as other bacterial and fungal mosquito control agents. Mosquito fish and other natural predators (WHO

1983), and botanicals such as neem cake, which is used to control agricultural pests, may offer additional control alternatives (R. Reuben, pers. comm.). All need to be stringently examined.

Environmental management. Environmental management may play an important role in control of arbovirus vectors and malaria vectors (WHO 1982). Draining ricefields at the appropriate times to reduce vector breeding has been tried with some success (WHO 1983), but unless the fields are level, numerous breeding puddles remain. At the other extreme, flooding fields to overflowing to flush out breeding sites significantly delayed and limited the epidemic size in the terai region of Nepal (unpubl. data). Both flushing, for which little excess water may be available, and drainage require efficient irrigation management, and neither can be accomplished without community participation.

Control of animal reservoirs. Virtually nothing can be done to control reservoirs. The population turnover of animals of principal importance in harboring arboviruses in ricefields is high. That introduces large numbers of non-immunes into the reservoir population each year. Water birds such as herons and egrets are major reservoirs but little can be done to control their breeding or their migration to new areas. Pigs are important for the maintenance of several viruses such as Tembusu, and Japanese encephalitis, but vaccination is considered impractical (Burke and Laeke 1988). Long-lived animals such as water buffalo and horses, once they are immune, may slow arbovirus transmission in that they attract large numbers of mosquitoes, but they must be sited between breeding areas and human habitation.

Summary and conclusions

1. Arboviruses transmitted in ricefield ecosystems are maintained primarily in zoonotic cycles of continuous transmission or transovarially and constitute a constant threat.
2. Infection with arboviruses associated with ricefield ecosystems results in a spectrum of human disease ranging from subclinical infection to acute encephalitis. Limited data indicate substantial levels of arbovirus transmission in several areas.
3. No prophylaxis or chemotherapy are currently available against arbovirus. diseases.
4. Long-term national and regional arbovirus surveillance needs to be established to gather data on the incidence of endemic disease and integrate them with epidemiological factors. The goal is to identify risks of epidemic outbreaks and the threat of epidemic spread to new areas, and to advise on intervention timing.
5. Epidemics of viruses, which are normally endemic, probably result from a buildup in vector population density as a result of weather (principally high summer temperature), agricultural practices, and water management. Reduction of vector density at the appropriate time is a requirement for disease control.

6. Control methods against arbovirus vectors need to be applied relatively widely around human habitation to be effective. Permanent reduction of vectors is probably not feasible by chemical methods alone or by integrated nonchemical control.
7. Reducing vector biting by house screening, use of bed nets, repellents, and health education may play an important role in reduction of disease transmission.
8. Despite increasing insecticide resistance, reduction in adult vector populations by insecticides may be effective during epidemics.

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Notes

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Author's address: C. J. Leake, Department of Entomology and Arbovirus Research Unit, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, England.

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Ecology of rodents associated with ricefields: implications for public health

A. A. ARATA

Rodents associated with rice cultivation and related human diseases are described. Rodents associated with rice vary taxonomically in Asia, Africa, and the Americas as do some of the diseases they transmit or harbor. Rice cultivation provides a specialized landscape with ecological elements favorable to rodents and disease transmission. There is, however, a scarcity of information on the role of rodents as disease reservoirs in the tropics generally and specifically in areas of rice cultivation. Several areas where additional information is required are suggested. These include details on population densities and seasonality, dynamics of host-pathogen-vector association, and differential susceptibility of rodents to human pathogens.

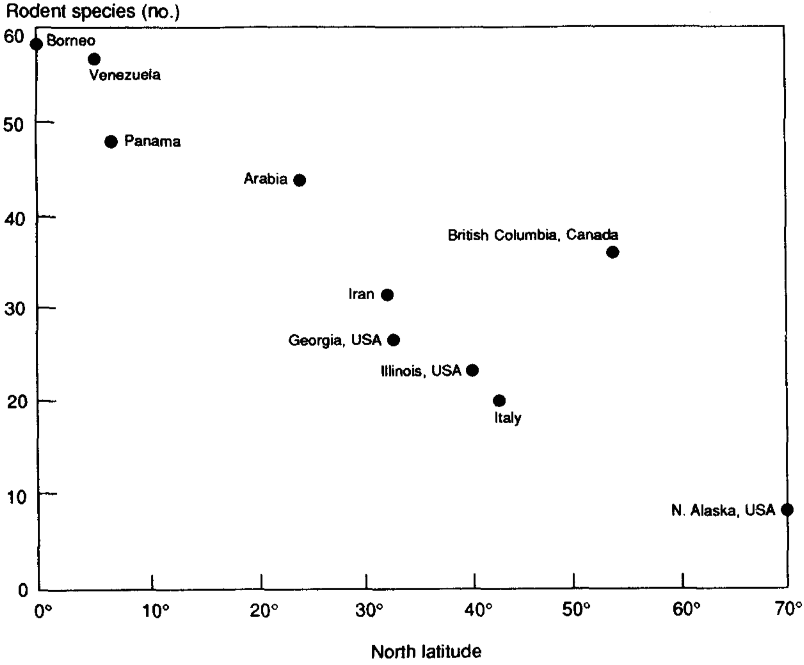
Approximately 75% of human caloric sources from plants are provided by grasses: rice, wheat, maize, other cereals, sugarcane, etc. (NRC 1982). Their high yields and great nutritional value, both having been increased by human selection, make the grasses attractive not only to man but to a host of insects and mammals—specially rodents. Morphologically and physiologically, most rodents are herbivores or granivores adapted to the use of all parts of grass plants—seeds, stems, and roots. The great evolutionary explosion of rodents occurred in the Miocene period during which the globe's grasslands—prairies, velts, steppes, pampas, and llanos developed.

Historically, human populations have concentrated in areas of cereal cultivation. As populations increased, humankind has systematically exploited natural grasslands and converted forest zones into derived grasslands of cultivated crops: Originally crops were of local origin, but now they are cultivated worldwide, wherever the yields are economically sustainable. Throughout this long history, rodents and humans have been closely associated. They are competitors for the same food and often are hosts of the same pathogens. It is in these two roles that rodents become deleterious to human health and to domestic animals.

Although this paper deals with the communicable diseases with which rodents are associated, it is essential to stress that malnutrition and the concurrent lowered resistance to common infectious and chronic diseases are among the most severe public health problems in the developing world. Field and stored crop losses attributable to rodents greatly exacerbate this problem. Crop loss estimates vary from negligible to 40% or greater. Estimates of 10-15% are common in global summary reports (Hopf et al 1976), and in studies in specific areas, such as the Philippines (Fall 1977; Schaefer 1975; UPLB RRC 1971, 1972, 1973, 1974). Whatever the precise figure in a given place or time, the losses most severely affect the poorest populations at greatest risk to infectious diseases. Such losses and other rodent damage problems have considerable economic effects (required food imports) thereby diverting funds that otherwise could be used for social and public health improvement.

Rodents associated with rice cultivation

Rice is a tropical or subtropical crop, and many of the climatic features necessary for its cultivation are conducive to the support of rodent populations as well. Although rodents may become disastrous pests of temperate agriculture, the number of species of rodents that inhabit the tropics is far greater (Fig. 1), as is their potential for disease transmission. The abundance of food and water, equitable temperatures throughout the year, human reduction of rodent predators (raptors, snakes, small



1. Relative abundance of rodent species from equatorial to temperate zones. Sources: Borneo; 0°N, 58 species reported (Medway 1965); Venezuela, 5°N, 56 species (Handley 1976); Panama, 7°N, 48 species (Handley 1966); Arabia, 24°N, 44 species (Harrison 1972); Iran, 32°N, 31 species (Lay 1967); Georgia, USA, 33°N, 26 species (Golley 1962); Illinois, USA, 40°N, 24 species (Hoffmeister and Mohr 1957); Italy, 43°N, 20 species (Toschi 1965); British Columbia, Canada, 54°N, 36 species (Cowan and Guiguet 1956); and northern Alaska, USA, 70°N, 8 species (Bee and Hall 1956).

mammalian carnivores), and adequate harborage in and around ricefields and storage areas provide most of the basic requirements to support rodent populations and assure their survival.

Figure 1, derived from a number of regional studies, illustrates the relative abundance of rodent species in temperate and tropical latitudes. The data are approximate as the tropical species are poorly known and new species are frequently identified in the tropics. In addition, the political units differ in size (Panama compared with Alaska) and the number of species may be affected by terrain, altitude, and diversity of habitats (British Columbia, Canada). Table 1 lists rodent genera that have been cited as causing damage to rice crops. Rice was first cultivated in Southeast Asia where the native rats (Rattus), mice (Mus), and bandicoots

Table 1. Rodents associated with rice cultivation by continent (after Hopf et al 1976).

Africa (Cameroon, Chad, Ghana, Liberia, Mali, Nigeria, Senegal, Sierre Leone)	
Arvicanthus	(Muridae)
Mastomys	(Muridae)
Rattus [a]	(Muridae)
Mus [a]	(Muridae)
Lophuromys	(Muridae)
Cricetomys	(Muridae)
Acomys	(Muridae)
Thryonomys	(Thyronomidae)
South Asia (Bangladesh, India, Nepal, Pakistan, Sri Lanka)	
Mus [b] (*musculus* and booduga)	(Muridae)
Rattus [b] (numerous species, especially in eastern part	(Muridae)
Millardia	(Muridae)
Bandicota	(Muridae)
Nesokia	(Muridae)
Meriones	(Cricetidae; Gerbillinae)
Gerbillus	(Cricetidae; Gerbillinae)
Tatera	(Cricetidae; Gerbillinae)
Southeast Asia (Burma, Indonesia, Philippines, Thailand)	
Rattus [b]	(numerous species) (Muridae)
Bandicota	(Muridae)
Mus [b]	(Muridae)
Americas	
Oryzomys	(Cricetidae)
Sigmodon	(Cricetidae)
Thomasomys	(Cricetidae)
Zygodontomys	(Cricetidae)
Hesperomys	(Cricetidae)
Holomys	(Cricetidae)
Heteromys	(Heteromyidae)
Liomys	(Heteromyidae)
Proechimys	(Echimyidae)
Rattus	(Muridae)

[a] Introduced to continent. [b] Native to continent.

(*Bandicota*) are still the most common pests. It should be noted that these genera of the Muridae are highly adapted to this area and have undergone an explosive evolution producing 63 recognized species of *Rattus* alone in Asia and the Pacific (Honacki et al 1982). Even within Southeast Asia and adjacent island groups, many murine species (*Rattus argentiventer* and *R. exulans*) have been introduced into one area from another through human activities. Many are known by name only and little information on ecology, disease-carrying potential, or distribution is available. Likewise, many of the names used in the public health and agricultural literature (the common use of *diardii, mindanensis, alexandrinus, niviventer, jalorensis, argentiventer, tiomanicus,* etc., as subspecific or specific names) are not taxonomically substantiated and may be incorrect, or at least not used for the same animal in different areas. Others, originally classified in the genus *Rattus* have been reassigned to other genera: e.g., *Maxomys* (=Rattus) *rajah* and *Sundamys* (=Rattus) *muelleri,* and others. There is a real need for proper taxonomic work to systematize the nomenclature along the lines proposed by Guy Musser in a series of works from 1969 to date, published in *Novitates* and the *Bulletin,* both of the American Museum of National History, New York.

As rice cultivation spread to the Middle East, Africa, and the Americas, local rodents (murids in Africa and cricetids, heteromyids, and echimyids in the Americas) became associated with its cultivation. *Rattus* and *Mus* were also introduced and established in these areas. Native rodents, because of their long association with grasslands, had little difficulty adapting to rice (roots, stems, seeds, and stored products). The facility is shown by the number of African and American genera listed in Table 1. Both upland and wetland rice in the new areas found readily available pest species. The list is certainly not comprehensive, but the increased number of forms in Africa and South America made it possible for new diseases to be associated, or potentially associated, with rice cultivation. For example, *Schistosoma japonicum* and *Angiostrongylus cantonensis* are helminths of Asia that do not generally occur elsewhere although *Angiostrongylus* has been reported from Cuba and Puerto Rico. On the other hand, Venezuelan equine encephalitis and Chagas' disease occur only in the Americas, and Lassa fever is exclusively African. Cutaneous leishmaniasis does not occur in Southeast Asia, but forms do occur in parts of Africa, the Middle East, and Latin America. The rodent reservoirs of all these diseases are now associated with rice cultivation in their respective regions. Other diseases (murine typhus, Q fever, and leptospirosis) are more cosmopolitan. Unfortunately, the data to correlate individual disease occurrences to specific crop zones are not extensive. Some diseases, such as Argentinean haemorrhagic fever (Junin virus), are exceptions, clearly associated with rodents infecting dry cereal crops (maize) and their storage. Some of the snail-associated helminth diseases such as Asian schistosomiasis are linked to rice growing. There is great possibility that new rodent-borne diseases will come to light. On the one hand our diagnostic tools (especially for microbial identification, both by isolation and seroimmunology) have become much better, and on the other the expansion of irrigated land will definitely increase, providing new areas, and new rodents, and possibly permitting new pathogens to emerge as disease entities.

That will likely occur in Africa and Latin America where only about 3% of the existing wetlands are currently in rice cultivation as compared with approximately 75% in Asia (Ganity 1988, this volume).

Diseases associated with rodents

In 1974, WHO published a partial list of human diseases associated with the 34 recognized families of rodents (containing 354 genera and 1,687 then-known species). Arata (1975) listed rodent-borne diseases by pathogen groups (Table 2). As mentioned earlier, some diseases are regional, others are cosmopolitan. The taxonomic groupings of the rodents associated with rice in Asia, Africa, and South America clearly demonstrate that rice cultivation, as one of the major agricultural endeavors, provides a particular landscape that is suitable for disease transmission, and various rodents have adapted to it. In mosquitoes, this adaptation has been at the species level. Distinct species of the three major vector genera *Anopheles, Culex,* and *Aedes* are found throughout the world filling ecologically equivalent habitats. With rodents, however, the diversification is at the familial level, with many genera and species filling the equivalent habitats. This makes it difficult to generalize about

Table 2. Representative diseases of humans associated with rodents.

Viral diseases
Crimean haemorrhagic fever
Omsk haemorrhagic fever
Russian spring-summer encephalitis
Western encephalitis
California encephalitis
Venezuelan equine encephalitis
Central European encephalitis
Argentinean haemorrhagic fever
Bolivean haemorrhagic fever
Lassa fever
Korean haemorrhagic fever

Rickettsial diseases
Murine typhus
Q fever
Rickettsial pox
Scrub typhus (tsutsugamushi)
Spotted fever group

Bacterial diseases
Brucellosis
Glanders
Plague
Listeriosis
Salmonellosis
Shigellosis
Tularemia

Spirochetal diseases
Endemic relapsing fevers
Leptospirosis
Rat-bite fever

Fungal diseases
Actinomycosis
Adiaspiromycosis
Histoplasmosis

Protozoal diseases
Cutaneous leishmaniasis
Visceral leishmaniasis
Toxoplasmosis
American trypanosomiasis
(Chagas' disease)

Helminth diseases (or genera)
Echinococcosis
Asian schistosomiasis
Capillaria
Hymenolepis
Angiostrongylus

Arthropod diseases
Chigger mite dermatitis
Rat mite dermatitis

rodents associated with rice cultivation, as it is a facultative adaptation. The major exception is the genus *Rattus,* native to Southeast Asia but introduced worldwide.

Because of this diversity, I have tried to reduce the major ecological components of rodent-disease ecology to 1) abundance, 2) contact with humans, and 3) susceptibility to disease agents, as the three most important areas that require study to elucidate the role rodents play in harboring and transmitting human pathogens. Unfortunately, but not surprisingly, there is not much systematically collected information on these subjects, especially in the tropics where rice is the major crop.

Ecology of tropical rodents associated with diseases

In medical entomology, the concept of vectorial capacity has been used for many years to quantitatively express the ability of a given species, in a given area, to transmit a pathogen from host to host (human to human, or another mammal to human). The formula employed (see Dye 1986) utilizes species abundance, movement, human biting disposition, and longevity (as two or more bites are required for transmission). A species' ability to maintain the pathogen in an infectious state is referred to as vectorial competence. These measures are, in essence, the sum total of our pathobiology investigations. If we consider then that reservoir *potential* would be an analogous measure for rodent species as reservoirs, the following bionomic components would be the most important for us, to arrive at a better understanding of the roles of rodents in the ecology of disease transmission.

Abundance

In areas where studies have been conducted, abundance is usually reported as number of animals per hectare, or a relative number captured (number per trap night) when comparing one area with another. Few data on tropical forms are available for comparison with the well-studied temperate rodent groups (Table 3).

What is shown, however, is that temperate-zone rodent populations are regularly subject to population fluctuation, seasonally and cyclically (as in northern microtines), whereas tropical rodent populations are relatively stable. The occasional *outbreaks* of tropical rodents reported (usually of the genus *Rattus*) appear to occur only where mankind has replaced native vegetation with cultivation, usually monoculture.

Seasonal variation in populations generally reflects the reproductive pattern. In a compilation of information on breeding patterns, French et al (1975) show that only 3 (30%) of 10 of the tropical species were periodic breeders, whereas 64 (94%) of 68 of the temperate species showed seasonal breeding patterns. The only examples of continuous breeding in temperate populations occurred in *Mus, Rattus* (2), and *Microtus* (*Microtus* may breed under the snow if food is adequate.) Turner et al (1975), working in Central Java, showed that female *R. exulans* bred all year. Monthly samples revealed that 40-86% (x = 69%) of the females taken were pregnant, lactating each month. Females in the study averaged more than 5 litters/year with an annual production of between 25 and 42 young.

Table 3. Comparative population estimates for tropical and temperate zone rodents (Fleming 1975, French et al 1975).

Genus	Home range (ha) or greatest distance (m)	Density (no./ha)	
		Seasonal	Outbreaks
Temperate forms (North America and Europe)			
Apodemus spp.	1-5 ha 50-100 m	5-20	45
Peromyscus sp.	1-2 ha	10-30	40-50
Arvicola sp.	50-100 m	5-10	~ 1,000
Clethrionomys sp.	0.8-1.0 ha	20-40	~ 250
Microtus sp.	0.5 ha	11-60	~ 1,300
Tropical forms			
Liomys			
(Panama and Costa Rica)	0.6 ha	4-11	N.D.[a]
Heteromys (Costa Rica)	0.6 ha	24	N.D.
Oryzomys (Panama)	N.D.	2.5	N.D.
Taterillus (Senegal)	N.D.	1-9	N.D.
Proechimys (Panama)	N.D.	3-8	N.D.
Rattus			
rattus (Venezuela)	N.D.	1-6	N.D.
rattus (Hawaii)	N.D.	20-64	N.D.
blanfordi (India)	N.D.	2.7	N.D.
wroughtoni (India)	N.D.	10	N.D.
exulans (Hawaii)	N.D.	–	49-185
exulans (Hawaii)	N.D.	0-30	N.D.
exulans (Pacific Is,)	N.D.	–	~ 90
tiomanicus (Malaya)	N.D.	–	250-500

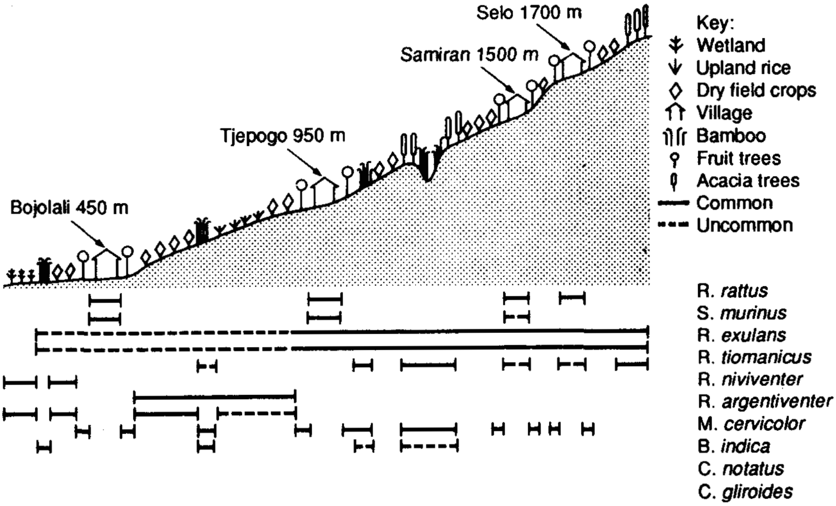
[a] N.D. = no data.

From a disease standpoint, this implies that in the tropics new young (susceptibles) are recruited into the population throughout the year at a more or less even rate. The converse is seen in the temperate zone where populations are markedly higher at certain periods. Tropical disease patterns therefore tend toward endemicity (stability) as opposed to epidemicity (fluctuation). This condition is reinforced in the tropics by the number of species (reservoirs and vectors) occurring, thereby offering the pathogen numerous alternate paths of survival.

Contact with humans

The degree of contact that a given rodent in a population has to humans is a function of overall abundance and lifestyle. Clearly, rodents living in and about ricefields and infesting houses and grain storage areas show a proximity as opposed to sylvatic rodents whose contact with humans is more casual or even random. However, contact with a given pathogen is also a function of the transmission cycle in which a vector may or may not be involved. Diseases such as leptospirosis, salmonellosis, and the arenaviral infections (Lassa, Bolivian, and Argentinean haemorrhagic fevers) can be transmitted directly by urine or fecal contamination of food and water and require no arthropod or snail vectors. In rice cultivation there is no lack of water contact. In those cycles requiring a vector (such as certain rickettsioses and viral encephalides), the contact between the rodent and human need not be great. Individual arthropods such as mosquitoes, which also breed in ricefields, may travel much farther than individual mammals. Others, such as ticks and mites, may travel considerable distances by means of several hosts. Therefore it is the potential movement of the pathogen that is of concern. Turner et al (1975) described this situation in his study of plague in Central Java, where one shrew *(Suncus)* and nine rodent populations had overlapping distributions while sharing two or more species of fleas that passaged the plague bacillus from fields and woods into the villages where different rodent reservoirs resided (Fig. 2).

Few studies in the tropics permit us to be specific or quantitative regarding rodent-human contact rates and disease transmission. We must remember that many of the diseases shared by humans and rodents are essentially rodent diseases (plague, the arenaviruses, numerous arthropod-borne encephalides, some forms of leishmaniasis, etc.) and as such are not dependent on the human for maintenance in their natural foci. Much of our information therefore is not specific to diseases associated with rice cultivation, but only to the rodents that come into contact with humans through cultivation. Botanically, cultivation alters climax vegetation to produce a high yielding ecotone. Because of the richness of species of potential vectors and reservoirs, the greatest concentration and contact with humans occurs in the tropics. Describing the phenomenon, however, does not explain its working. For that, we need more quantitative information on the components of the transmission cycle.



2. Host distribution in the Bojolali plaque focus, Central Java, Indonesia (Turner et al 1975).

Differential rodent (reservoir) susceptibility to pathogens

The differential susceptibility of rodents (species, genera, or families) to specific pathogens, or pathogen strains has not received adequate attention in ecological studies of rodents as reservoirs. When two or more potential reservoir species occur in the same area, ecological observations usually favor, as the prime suspect, the one in closest contact with humans or the one of greatest population density. This may be correct, but it is equally likely that one species serves as a maintenance reservoir and the other as the amplifying reservoir. This has been shown in studies on plague reservoirs in Central Asia and Java (Kalabukhov 1970, Muul 1970, Turner 1975). Arata and Gratz (1975) showed that the arenaviruses of the Americas were all associated with one group of cricetine rodents (Hesperomyini), despite the varied and complex rodent fauna that exists in the area. There are fewer cricetines in the Old World and the arenaviruses there (lymphocytic choriomeningitis in Eurasia and Lassa in Africa) are carried by murids. Hantaan virus (a bunyavirus causing haemorrhagic fever with renal syndrome) in Korea has been identified in only one of two species of the murid *Apodemus,* and not at all in sympatric microtine rodents. In Africa, there are many species of murids and several *Mastomys,* but only *Mastomys natalensis* populations have been implicated in transmission of Lassa fever.

Classic work with tularemia was done by Olsuf'ev and Dunaeva (1960, 1970), classifying, by field observations in natural foci and laboratory experiments, mammals into three groups according to the degree of susceptibility and infective sensitivity to the pathogen *Francisella tularensis.* (For a discussion, see Arata et al 1973.)

In South America there appear to be two general classes of Venezuelan equine encephalitis virus strains: those that are not pathogenic for equines and those that are. Both strains cause illness and sometimes mortality in humans. The epidemiology of the infection and the role of wild animals with regard to strains causing epizootics in equines are not known, but strains not pathogenic for equines are endemic in sylvatic rodents. They are transmitted by mosquitoes of the genus *Culex* (MacKenzie 1972).

Other examples could be given, but it is clear that determination of the reservoir potential of any group of rodents cannot be based only on ecological parameters, but on microbiological ones as well.

Conclusions

Although we have lists of rodents that infest ricefields and know that those rodents are associated with some of the important zoonotic diseases of their respective tropical regions, we do not have adequate quantifiable information on the transmission dynamics of rodent-borne diseases. That makes it difficult to assess the magnitude of the public health problems involved because the diseases are generally not reportable. As a result, the quality of surveillance is poor.

Rodent ecology in the temperate zone has reached a stage where, at least for agriculture, modeling and prediction of outbreaks is possible and potential losses can be prevented or reduced (Arata 1977). That is not the situation in the tropics, and research in the following areas must be conducted:

- Taxonomy of tropical rodents needs clarification with dissemination of practical field-tested keys for identification, resulting in the use of correct nomenclature for animals important to agricultural and public health workers.
- Basic ecological studies to determine reproductive rates, seasonality, movements, and population densities of rodents are required. Work is also needed to develop the proper techniques to be used in tropical studies.
- Studies are needed on host-pathogen-vector associations, especially to define what happens between outbreaks of human cases, and which rodent species are the maintenance and amplifying hosts.
- Systematic microbiological studies on differential susceptibility of known or potential rodent reservoirs to different pathogen strains are necessary.
- Epidemiological studies are needed to assess the levels of morbidity that can be attributed to rodent-borne diseases and the level of disability and economic loss to the affected human populations.

It is estimated that only about one-seventh of the world's arable land is irrigated, yet this area accounts for more than one-third of the total value of global crop production. To increase the desired doubling of food output in developing countries within the last 20 years of this century, at least half of that increase will have to come from irrigated land. This will call for further enormous investments in irrigation over the next two decades. One estimate is for approximately $230 billion at 1975 prices (WHO 1982).

Such an increase in cultivated land, probably much of it in rice, will enormously exacerbate the potential for outbreaks of rodent-borne diseases. Before that occurs, we should be gathering the ecological information required to prevent or reduce their impact in the developing world.

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Notes

Author's address: A. A. Arata, Vector Biology and Control Project/USAID. Arlington, Virginia 22209, USA.

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Integrated mosquito vector control in large-scale rice production systems

D. A. Dame[1], R. K. Washino[2], and D. A. Focks[1]

Ricelands in the United States produce floodwater *Aedes* and *Psorophora* spp., whose soilbound eggs hatch shortly after flooding to producedistinct broods of mosquitoes, and standing-water *Anopheles, Culex* and, *Culiseta* spp., which oviposit on the water surface from which mosquitoes continuously emerge. Community-sponsored mosquito control programs commonly include aerial application of *Bacillus thuringiensis* (H-14) or methoprene, combined occasionally with the introduction of mosquito fish against larvae, and aerial and ground ultralow volume applications of fenthion, malathion, naled, or resmethrin against adults. Economical surveillance methods are utilized to support decisions on placement and timing of control applications. New biological control agents that might be effective in riceland situations include fungi, bacteria, and microsporidia; some of these agents could be available within 3-5 yr. The number of new candidate insecticides has diminished markedly in recent years, a trend that is expected to continue. To improve the capability for control, more ecological and biological information on mosquito vectors of disease is required. Models for predicting riceland mosquito populations based on annual availability of irrigation water and rainfall are discussed. Computer simulation models are being devised and utilized because they greatly assist in the selection and timing of control-strategy components.

Rice is one of the major crops in the United States that require extensive irrigation. Management of rice production involves agricultural practices and concepts directed toward the harvest of high-quality, cost-effective crops. The grower is not preoccupied with the concurrent production of mosquitoes, which often far exceeds the densities that occurred before turning the land to rice culture. However, the rice producers and the residents of communities in rice-growing areas of the U.S. have become increasingly aware of the irritation and potential health hazard that riceland mosquitoes have created for themselves and their livestock.

The protection offered by adequately constructed homes, properly screened to bar the entrance of mosquitoes, no longer satisfies the urban residents of agricultural communities. Throughout the rice-growing regions, more and more communities are supporting active control programs with their tax dollars. The control programs are complex and require communitywide effort and support. That these programs exist is a tribute to countless research and extension activities that have been conducted in the U.S. and throughout the world in the last few decades; these efforts have created a technology that is adaptable to the human-made problem of mosquito production in irrigated croplands. Much of the text of this paper was prepared with direct reference to this body of knowledge, which is detailed in the annotated bibliography on riceland mosquitoes prepared by collaborators in the Riceland Mosquito Management Program (Paine 1983).

Integrated control has been defined as the utilization of all appropriate technological and management techniques to bring about an effective degree of suppression in a cost-effective manner (Mather and That 1984). In the US. and elsewhere, mosquito control provides excellent examples of integrated pest management (IPM). A variety of techniques have been used: source reduction, water management, personal protection, biocontrol, and insecticides in concert to obtain the desired suppression.

In the rice-growing areas of the U.S., the elimination of malaria by suppressing the vector with DDT in the post-World War II era led the way to extensive insecticide use against both mosquitoes and agricultural pests. Chlorinated hydrocarbon, organophosphate, carbamate, and more recently, synthetic pyrethroid insecticides have been used extensively enough in the U.S. to have produced resistance in some riceland mosquitoes. The lessons learned have accentuated the awareness of the need for IPM strategies that preserve both the efficacy of the available chemicals and the integrity of the environment without adversely affecting humans, livestock, or other organisms.

In recent years there has been a marked reduction in the use of mosquito toxicants that persist in the environment, e.g., the arsenical Paris green and most of the chlorinated hydrocarbon insecticides. The use of crude petroleum oils has given way to more refined products that are effective at lower application rates.

At the same time, new and safer pesticides have been registered, and promising new biocontrol agents are being developed for use in many types of breeding habitats, including ricelands. Extensive use has been made of the insect growth regulator methoprene in irrigated habitats, and *Bacillus thuringiensis* var. *israelensis* (designated serotype H-14 by deBarjac and often abbreviated as *Bti*) has become a practical microbial toxicant for control of riceland mosquito larvae. While the chitin synthesis inhibitor diflubenzuron has not been registered for control of mosquitoes in croplands, the monomolecular surface film Arosurf has been cleared for riceland use.

Riceland mosquitoes in the U.S.

Much like in rice culture throughout the world, ricelands in the U.S. produce two major types of mosquitoes: the floodwater mosquitoes, whose eggs hatch shortly after flooding and soon produce a single flush of adults (*Aedes* and *Psorophora*); and the standing-water mosquitoes that oviposit on the surface of the water and produce adults throughout the flooded period (*Anopheles, Culex,* and *Culiseta*). Between these two types of mosquitoes, breeding occurs in many parts of the ricefields, including canals, levee ditches, on pans and in ruts created by harvesting equipment or in depressions created by cattle hooves in fallow fields, and in reservoirs maintained for flooding the fields. The frequent presence of livestock near the fields provides a ready source of blood and enhances the likelihood of mosquito reproduction.

New broods of floodwater species will hatch almost any time that the water level is raised by irrigation or rainfall, but especially after the level has been allowed to fall and fresh eggs have been deposited at the levee edge of the plantings in the moist soil above the receding waterline. The standing-water species, on the other hand, are less opportunistic; water quality determines to a great extent when each species will move into the habitat. Water quality, in turn, is affected by cultivation practices that may modify the pH, clarity, weed composition, and buildup of parasites and predators of the mosquitoes, Furthermore, ovipositional behavior may be influenced by the status (height, density, color, leaf characteristics, shading efficiency, etc.) of the rice planting.

Rice areas exceeding 4,000 ha are found in Arkansas, California, Florida, Louisiana, Mississippi, and Texas. Each area has local conditions and cultural methods that affect mosquito species composition and population dynamics. In Florida, rice is grown in alternation with sugarcane, and usually is planted only once in 5 yr. Here the soil is so porous that new water must be pumped continuously onto the fields from the adjacent canals; cessation of pumping results in loss of standing water within a few hours. In Arkansas, new water is added to the pans every few days to replace that lost to percolation, evapotranspiration, and seepage through the levees. In Louisiana, after the main crop has been harvested a second (ratoon) crop is produced from the stubble. In California, some fields are flooded from deep wells with cold water that has a high concentration of dissolved salts, whereas others are flooded with warm, standing surface water with greater biological productivity.

In California, the major targets of control in ricelands are the standing-water species *Anopheles freeborni* Aitken and *Culex tarsalis* Coquillett. Both are vectors; *Anopheles freeborni* is associated with occasional transmission of introduced vivax malaria and *Culex tarsalis* is the primary vector of both western equine encephalitis and St. Louis encephalitis. In the southern areas *Psorophora columbiae* (Dyar and Knab) is the primary floodwater species and is distributed throughout the rice-growing area. The major standing-water species are *Anopheles quadrimaculatus* Say, recently identified as a complex of two or more species (J. A. Seawright, pers. comm.), *Anopheles crucians* Weidemann, *Culex salinarius* Coquillett, and *Culex erraticus* (Dyar and Knab). All of these species are annoying to humans and livestock in ricelands.

Current chemical control in the U.S.

Larvae

Larvicidal control measures that are compatible with grower operations usually require the application of chemicals without resorting to actual entry into the ricefield. In most instances the larvicide is applied by aircraft or by metering it into the irrigation water. The larvicides most commonly applied to ricefields are *Bti,* methoprene, and parathion. Table 1 gives a general listing of larvicides registered for mosquito control.

The application of *Bti* to ricefields in Louisiana is often accomplished by a drip technique, which is calibrated to match the flow of irrigation water into the fields (McLaughlin and Vidrine 1984). As the water moves across the planted areas and through the cuts in the levees, the *Bti* moves along with it. Thus, the bacterial spores containing the toxin are present when the larvae of *Psorophora columbiae* hatch shortly after flooding. Except for areas in which water movement is restricted because of hydrological characteristics of the field, the level of control is usually high. Where flow is restricted or where the water backs up into corners of the fields, control is reduced. Because this floodwater species hatches in response to flooding, the brood can be controlled by a single treatment (about 1.2 liters/ha) with this technique.

Treatment for controlling subsequent populations of *P. columbiae,* which may occur in response to changes in water level, and of standing-water species such as *Anopheles quadrimaculatus,* usually requires aerial application. Currently, the preferred insecticides for rice are *Bti,* parathion (used primarily in California), and the IGR methoprene. Even in fairly mature rice stands, application rates of only 220-290 ml *Bti*/ha provide a high degree of larval control. To maintain suppression of the larval population with *Bti,* applications are required every 10-14 d.

To obtain adequate control of standing-water mosquito larvae with methoprene, application rates of 22-29 ml ai/ ha are required. Unlike *Bti,* which acts within 24 h after ingestion by the larvae, the effect of methoprene is delayed until the pupal stage. Although an overdose of methoprene can result in some early larval mortality, the most sensitive period is during the late 3d and early 4th instar. Exposure at this sensitive stage is followed by pupal rather than larval death. Formulated as a slow-release encapsulated product, methoprene persists for 7-10 d. Thus, the normal interval between treatments is similar to that of *Bti.*

Similar control is obtained with parathion applied at 112 g ai/ha. Parathion degrades rapidly, but because it is effective against all larval stages, application intervals are similar to those of *Bti* and methoprene.

Methoprene and *Bti* are both highly selective. In the riceland environment, the only group that is significantly affected is the Culicidae. Each of these two larvicidal approaches is compatible with natural biocontrol agents present in the ecosystem and with the concurrent introduction and augmentation of selected biocontrol agents. Therefore, a wide variety of IPM strategies can be considered in large-scale riceland mosquito control, dependent primarily on the availability of suitable biocontrol agents for augmentation.

Adults

In the U.S., control efforts against adult mosquitoes commonly are made after the adults have migrated to the communities from the breeding sites in the fields. Little or no effort is put into residual applications for the control of resting riceland mosquitoes. The primary approach relies on aerosol application using ground or aerial ultralow volume applications (ULV) and, less frequently, ground thermal fog. Aerosol application was reviewed by Mount (1986).

Ground ULV and thermal fog applications are accomplished by truck-mounted aerosol generators. The efficacy of ground applications is dependent upon street layout, wind, temperature at and above ground level, vegetative cover, target species, droplet size, etc. Of the insecticides registered for this use in the U.S., the most commonly used are fenthion, malathion, naled, and resmethrin. Minimum effective application rates of these and other available adulticides are listed in Table 1.

Aerial application requires somewhat higher treatment rates than ground application, and the efficacy of the treatment is more subject to many of the same factors that affect ground application. As with larvicidal treatments, applications are subject to federal tolerance levels for the amount of insecticide residue remaining on the target crop at harvest or on adjacent crops. Also, as with larvicides, phytotoxicity of certain formulations must be avoided. However, when done properly aerial treatments generally are more effective than ground applications. Specific insecticides and minimum application rates are presented in Table 1.

General considerations

Surveillance. Regardless of the type of chemical control strategy, standard operational procedures include surveillance to monitor populations of the target species. Surveillance is usually restricted to the most rapid and simplest method to determine whether insecticide application is warranted considering the agricultural, meteorological, hydrological, and seasonal factors that influence mosquito populations.

Table 1. Minimum application rates for insecticides available for general mosquito control in tho United States.

Insecticide[a]	Larvicide (g ai/ha)	Adulticide	
		Ground ULV (mg ai/min at 16 kph)	Aerial ULV (g ai/ha)
Bendiocarb	–	9	–
*B*ti	0.22[bc]	-	–
Chlorpyrifos	14	12	–
Fenthion	58[c]	17	56[c]
Malathion	560	54[c]	216[c]
Methoprene	22[c]	–	–
Methoxychlor	224	–	–
Monomolecular film	1.85[b]	–	–
Naled	–	15[c]	101[c]
Oil	27.55[c]	–	–
Parathion	112[c]	–	–
Propoxur	–	90	–
Pyrethrins/PBO	–	6/30	–
Resmethrin	–	19	–
Resmethrin/PBO	–	16/48[c]	8/24[c]
Temephos	18	—	—

[a] PBO = piperonyl butoxide. [b] liters/ha. [c] Currently used against riceland mosquitoes.

To determine larval densities, dipper surveys are usually conducted at the edges of representative ricefields. Biweekly treatments make it impractical to sample any given field intensively to determine precise larval distribution and density.

The success of the strategies based on these estimates is shown by subsequent collections of adults in the breeding areas and surrounding communities. Adult mosquito relative abundance usually is monitored with light traps, often enhanced with carbon dioxide emanation from dry ice placed at the trap site. Even with a minimum number of judiciously located sites, nightly monitoring at all regular stations is seldom attempted. Observations from these surveillance activities are reinforced by the residents, who freely register their assessment of the control that has been achieved.

Insecticide resistance. In some areas insecticide resistance is an important consideration, e.g., in Arkansas, where *Anopheles quadrimaculatus* (Roberts et al 1984) is highly resistant to malathion, probably as a result of exposure to agricultural applications of organophosphate insecticides. In California, several species of standing-water and floodwater mosquitoes have developed insecticide resistance to more than one class of insecticide as a direct result of applications for the control of larval populations. In Florida, where still different conditions prevail, the development of widespread resistance to nonchlorinated hydrocarbon insecticides has been delayed largely by avoiding the use of the same class of pesticide to control both larval and adult stages. Nevertheless, in each of the rice-growing areas of the U.S. there are a variety of compounds still effective against the local target species.

Migration from alternative breeding sites. Although rice production may exacerbate the problem of annoyance and mosquito-borne disease transmission, the offending species were, of course, present before rice cultivation began. Irrigation and water management practices have created a situation in which some types of mosquitoes thrive. Those same species are found in their natural habitats throughout their breeding seasons, only part of which includes rice cultivation months.

Control strategists must deal with mosquitoes that emanate from the alternate breeding sites, migrate to residential areas of rice-producing communities, and oviposit in the ricefields. Some species that inhabit ricefields are capable of fairly extensive dispersal. Meteorological conditions commonly have a more significant influence on the abundance of mosquitoes originating from the alternate breeding sites than on the abundance of those originating in the managed ricefields. Control and surveillance may occasionally have to be extended to areas beyond the ricefields to realize or protect the benefits achieved by control efforts in the fields and communities.

Economics. The cost of controlling riceland mosquitoes in the U.S. varies greatly from site to site and depends on the intensity of the operation and the magnitude of the problem. For example, in Jefferson Davis Parish (county), Louisiana, control of larvae and adults of ricefield-breeding mosquitoes costs about $20.00 annually for each of the 33,000 inhabitants. About 27,000 ha are planted to the first rice crop with parts of the riceland being planted to a second crop. Farther north, where the cropping season is not long enough for a second crop, the city of

Stuttgart, Arkansas, with a population of 12,000, annually spends about $13.00/inhabitant for larval and adult mosquito control.

Biological control in the U.S.

The magnitude of the ricefield as a mosquito habitat and the moderately long duration of the rice-growing season (4–5 mo) call for a biological control agent that exhibits long-term persistence or the ability to self-perpetuate in the aquatic habitat of the mosquito larvae. *Gambusia affinis* (Baird and Girard) or mosquito fish is still the only demonstrated biological control agent presently used for ricefield mosquito control (Hoy and Reed 1970,1971; Hoy et al 1971).

Where they are used, the fish are introduced each year into ricefields shortly after initial flooding. Once established, several broods may be produced during the summer months. Approximately 750 fish/ha gives effective control (Hoy et al 1971). Stocking fields 15-25 d after seeding appears to give the best fish population growth and mosquito control (Farley and Younce 1977). Haas and Pal (1984) report *G. affinnis* 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. Although this fish is considered hardy and adaptable, careful handling is imperative for trapping, transporting, and release (Coykendall 1980, Meisch 1985).

Natural populations of *G. affinis* do not reproduce during the winter and often suffer considerable die-off due to cold weather. It is difficult to obtain sufficient supplies of fish to stock permanent or semipermanent mosquito habitats, including ricefields, early in the year. Developing an aquaculture system to optimize production of mosquito fish during the winter to meet the demand early in the spring and summer has been the focus of recent research (Busack and Gall 1982, Busack 1983).

Survival of mosquito larvae from first instar through the pupal stage in ricefields varies from 2 to 5% (Mogi et al 1984,1986; Northup and Washino 1983; Service 1977) and much of the natural mortality is attributed to natural predators (Miura et al 1978, Mogi 1978, Service 1975, Washino 1981). It is, however, difficult to determine which predator or groups of predators are the most important; and that may vary considerably from one geographic area to another.

Application of U.S. methods to riceland mosquito control worldwide

Strategies for the control of riceland mosquitoes depend on social, fiscal, and political factors as well as on the characteristics of the mosquito species present and the management practices of rice cultivation. Perhaps the most significant reality in modern vector control is that it must be organized at the community level or higher.

Large-scale rice production can be expected to intensify vector activity and abundance regardless of location. The issues of control strategies and funding can be resolved only at the governmental level. This is a direct result of the many interacting factors that are involved, i.e., breeding and dispersal characteristics of the mosquitoes, prevalence of mosquito-borne disease, extent of the breeding areas and size of the affected communities, insecticide resistance, methods of surveillance, funding sources, etc.

The control strategies used in the U.S. are adaptable to rice production areas throughout the world. Specific strategies are determined locally and are influenced by the factors just mentioned. Residual deposits of insecticides, not broadly utilized in the United States, offer an additional component for consideration when planning local strategies. Furthermore, methods currently used elsewhere may be excellent candidates for development as components of strategies in the U.S.

Research on control methods

Chemical control

Research on new chemicals for use in mosquito control programs has been continuing steadily, although there are fewer new materials now than in previous decades. Insect growth regulators, synthetic pyrethroids, and microbial insecticides are being developed for inclusion into the list of available compounds. However, recent years have reconfirmed the realization that few materials will be developed by industry solely to satisfy the mosquito control market. Because of stresses related to human and environmental hazards encountered by the chemical industry, only those compounds that present a meaningful probability for adequate financial return reach the final stages of development for registration. These are not always the selective and specific materials that were envisaged two decades ago; more often they are the broad-spectrum compounds that can command a diverse market.

The ability of scientists and operational managers to learn how to improve the control of riceland mosquitoes rests not only on the development of new compounds. It must also rely heavily on a better understanding of the biology, ecology, and distribution of the target mosquitoes. Research on mosquito behavior and population dynamics must be fostered to learn to utilize more effectively the tools that we now have at our disposal. Worldwide experience in vector control has clearly shown the need for a better understanding of the factors that control the dynamics of mosquito populations.

Biological control

The major concern on how to introduce a biological control agent such that a sustained level of activity is exerted throughout the 4- to 5-mo breeding season has precipitated consideration of several agents.

Three 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. Factors affecting oospore germination are being intensively investigated. *Romanomermis culicivorax*

Ross and Smith, because of its demonstrated recycling and apparent resistance to desiccation during winter, has been investigated in California ricefields (Kerwin and Washino 1986b, Westerdahl et al 1982). Minimal parasite dispersal from the point of application in ricefields as well as the labor required for mass rearing in vivo prohibit serious consideration of the fungus for now.

Much of the research on biological control of mosquitoes has focused on the microbial approach, summarized by Lacey and Undeen (1986). The current use of *Bti* for control of riceland mosquitoes was discussed earlier. In addition to *Bti,* the high levels of mortality produced in several culicine and anopheline larvae without undue effect on nontarget organisms, and the persistence of prolonged larvicidal activity in several virulent strains of *B. sphaericus* Neide, make this bacterium a viable candidate for testing in a ricefield habitat.

A systems approach to epidemiology and control

The high densities observed for many riceland mosquito species are a result of their successful exploitation of the diverse riceland habitat, which to a greater or lesser degree is influenced by humans. For this reason, the riceland mosquito problem is considered a good one for successful development of IPM strategies in the U.S. Because IPM is complicated, a systems approach is a necessary adjunct to research efforts in that effective IPM programs may require modifications of crop and animal production practices as well as mosquito control programs. This is especially true for the more complicated problem of developing integrated systems to control the diseases transmitted by riceland mosquitoes.

A central element in a systems analysis of the complex rice agroecosystem is the creation of models of the system. Although various approaches, methods, and types of models can be used, there are several common reasons for modeling. Models summarize what is known about a particular system and, as such, highlight areas where additional or better information is necessary. Also, they can be used to predict mosquito abundance or rates of transmission of a mosquito-borne disease, and they give insight into the dynamics of a system that is the product of multiple, nonlinear, and complex relations. In the context of mosquito-borne diseases, perhaps the greatest impetus to the creation of models is the need to study long- and short-term effects of various control strategies, such as modifications to agricultural practices and vector control.

Washino and Thomas (1986) developed regression models to predict average summer abundance of several rice-associated mosquitoes (*Anopheles freeborni, Culex tarsalis,* and *Aedes melanimon* Dyar) in Sacramento Valley, California. This area does not receive sufficient summer rainfall to produce major populations of these mosquitoes. Rather, the mosquito problem arises from snow melt, which drains from the surrounding mountains through the valley and is used for rice irrigation. One goal was to identify environmental variables such as temperature, depth of snowpack, and rice hectarage, which correlated with mosquito abundance.

Because these variables can be measured in the winter and spring before the mosquito season, an additional objective was to determine if measurements of these variables could be used to predict, with reasonable confidence, impending encephalitis outbreaks or abnormally high mosquito densities. Predictive capabilities would allow public health and mosquito control agencies time to prepare for the upcoming mosquito season. The study indicated that several environmental variables may be sufficiently correlated with mosquito abundance to allow useful predictions. Rice area was the single variable most consistently correlated with mosquito abundance. Snowpack, as expected, also related to subsequent mosquito densities. However, no single variable was sufficiently predictive to serve as the sole basis for forecasts.

Having identified predictive variables by correlation analysis, regression equations using several dependent variables were then developed. These models produced predictions remarkably accurate and consistent with the observed 1954–79 populations. It would appear, with the exception of the years 1978 and 1979, that the forecasting models developed would be completely satisfactory for averting unexpected mosquito pest and disease outbreaks. It is important to realize that this type of analysis is possible only for areas where sufficient historical dataexist; in this example, more than 20 yr of collection records were available. For 1978 and 1979, the models considerably underpredicted the actual mosquito populations for several areas within the valley. This was considered unacceptable, given the intended use of the predictions. The source of the discrepancy is being studied using data through 1983. It may be due to new factors affecting mosquito populations that were absent in preceding years. Keeping in mind the data requirements and the need for a consistent system, it appears that this method could be profitably used in other rice-growing areas of the world.

Using simulation methods, Focks and McLaughlin (1986) are attempting to develop a comprehensive model of the rice agroecosystem. The model is designed to aid in developing, improving, and evaluating appropriate IPM strategies for any rice-growing region of the world. Water balance of a region determines the spatial and temporal distribution of oviposition sites and permanent and temporary pools available to the mosquito. Thus, the framework of this model is the description of the water balance in a representative area, e.g., 1 km^2. Required inputs include land use such as rice and nonrice area; soil characteristics such as runoff rates, porosity, and ponding depths; weather such as rainfall, pan evaporation rates, and air temperatures; and agricultural practices such as flooding and harvesting dates and water sources.

The initial model, completed in 1987, describes the population dynamics of the temporary-pool mosquito, *P. columbiae,* in several rice-growing states in southern U.S. The mosquito population is simulated with a dynamic life table approach in which the computer keeps track of the numbers of the various life stages. The model utilizes data from the literature and insights from researchers and operations managers who are working on the riceland mosquito problem. Inputs include daily maximum and minimum air temperatures and photoperiod as factors that affect larval development time and the production of diapausing eggs, and host density, which affects adult survival and fecundity. The accuracy of the model has been verified using light trap and egg density data from southern Louisiana.

Simulation studies have been initiated on the effects of adulticide and larvicide application, the role of host management, and the destruction of overwintering eggs on the population dynamics of *P. columbiae.* These simulation studies indicate that although ground or aerial ULV applications of insecticides temporarily reduce local populations, they have little impact on the overall dynamics of *P. columbiae.* They also suggest that the effective treatment of cattle with a residual insecticide at one or more key times during the year could drastically alter subsequent populations of this mosquito, which feed primarily on cattle in southern US.

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Authors'addresses: D. A. Dame and D. A. Focks, U.S. Department of Agriculture ARS, Insects Affecting Man and Animals Research Laboratory, P.O. Box 14565, Gainesville, Florida 32604, USA, R. K. Washino, Department of Entomology, University of California, Davis, California 95616, USA.

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Integrated mosquito control in small-scale rice production systems

C. H. SCHAEFER AND M. V. MEISCH

Integrated control is the utilization of all available control methods in an optimal combination. This can allow for a long-term solution to minimizing losses due to rice pests while limiting the incidence of vector-borne diseases. Also, minimum dependency on chemical control reduces selection pressure and delays the onset of insecticide resistance. This approach is highly sophisticated, requiring detailed knowledge of all aspects of the crop, associated pests, and the parasite and predator complex. A high degree of interdisciplinary cooperation is essential for planning and executing management strategies. While this appears desirable, it is difficult to achieve and probably will require a single management structure responsible for both rice production and pest and vector control. To implement integrated control on ricefields, the population levels of each key rice pest, vector, and predator species must be monitored. This requires adequate personnel well-trained in aquatic biology. Selective chemical control agents, which do not disrupt the agroecosystem, must be developed for use when biological and environmental control fail.

This paper emphasizes the concept of integrated control. Let us examine the definition of integrated control to avoid misunderstandings.

The integrated control concept was proposed by Stern et a1 (1959), and defined as applied pest control, which combines biological and chemical control. Chemical control is used when necessary and in a manner that is least disruptive to biological control. It includes naturally occurring biological control and manipulated or introduced biotic agents. Later, the definition was modified to include the integration of all crop protection procedures. We use the term integrated control to mean the optimum combination of all available control methods.

Advantages and disadvantages of integrated mosquito control

Before considering integrated mosquito control in rice, we must first acknowledge that mosquito breeding is a by-product of rice production. For example, an extensive treatise on rice production (Luh 1980) did not mention a single mosquito or mosquito problem. Even today, many rice producers do not regard the mosquito problem as one for which they are, or should be, responsible. Only after the problem is recognized can mosquito control be incorporated into the overall management strategies of rice production.

Advantages of integrated control

Integrated control could lead to a long-term solution to the problem of minimizing yield losses due to rice pests and at the same time limit the incidence of vector-borne diseases.

The optimum combination of available management strategies would minimize the use of pesticides, lower production costs, and disrupt the environment the least. Reducing selection pressure for insecticide resistance would be an added benefit of reducing pesticide use.

Disadvantages of integrated control

The high degree of interdisciplinary cooperation required in planning and implementing integrated control is difficult to achieve. Integrated control is complex and requires a detailed knowledge of all aspects of the crop, associated pests, and the interaction of management strategies. The taxonomy and ecology of pest, vector, and associated predator/parasite species must be determined.

The maximum population or threshold of a given pest that could be tolerated without significant crop loss must be established, and the mosquito threshold that could be tolerated without causing a disease outbreak must be defined. Establishing these thresholds requires methods to monitor the populations of each key pest, vector, and predator species. Monitoring must be continuous to determine the need for and timing of pesticide treatments.

Ricefields cannot be considered in isolation. Adjacent lands such as fallow fields, irrigation canals, and drainage ditches harbor pests and disease vectors; they must be monitored as well as the ricefields themselves.

Agents used to control mosquitoes in rice production systems

Chemicals

There is little doubt that chemical agents will always play an important role in rice production. They include insecticides, herbicides, fungicides, and fertilizers. They must be selected with care because of their direct and indirect effects on nontarget organisms. The impact of each chemical agent must be considered in relation to the overall ecosystem. Those that have the least deleterious effects should be selected, even though their unit cost might be higher than others available. Research on existing or new chemical agents must consider not only their efficacy but also their effects on nontarget organisms and their persistence. For example, the fungicide triphenyltin hydroxide, which was being considered for wide use on rice in California, killed all aquatic fauna when applied at the suggested use rate of 1.1 kg/ha. The toxicity of this agent to mosquito fish persisted for 15 d. A single dose, applied at the midtillering stage, significantly delayed the potential for reestablishment of effective levels of mosquito fish before the mosquito larvae reached maximum seasonal abundance. In contrast, the mosquito population quickly resurged (Schaefer et al 1981).

Some chemical side effects can be tolerated without such severe consequences. Early-season application of the herbicide thiobencarb at the suggested rate of 4.5 kg/ ha caused 25% mortality to mosquito fish. The toxicity, however, did not persist and the side effects were minor. Also, the stocking of mosquito fish could have been delayed a few days to further reduce mortality without seriously delaying seasonal development (Schaefer et al 1983).

Interactions of chemicals can result in other problems. For example, the application of synergistic combinations such as the herbicide propanil and the insecticide parathion causes phytotoxicity. Drift from this combination can damage some crops adjacent to ricefields (plums). Thus, propanil is prohibited in large areas of California.

Mosquitoes are generally sensitive to insecticides and are controlled at dosage rates greatly below those used for most insect pests of rice. Some chemicals being evaluated as mosquito-larvicides are effective at rates of 0.01 kg/ ha or less. Generally, such low dosages minimally affect nontarget organisms. This raises the possibility of reducing a high population of mosquito larvae without disrupting the predator complex of rice insect pests. Applying insecticides at relatively high rates (1.0 kg/ ha or greater) required to control most pests of rice may also control mosquitoes. These high application rates, however, are likely to reduce mosquito predator populations and permit the rapid resurgence of mosquitoes.

The development of selective chemical agents would enhance the use of integrated control. The commercial development and use of generally nonselective chemicals, which still are common, reduce the possibility of integrated control.

Manufacturers will produce products specified by the user as long as the cumulative market is sufficient. Because the total rice market is large, there is an opportunity to develop specifications for chemical agents that would be acceptable for use in ricefield management. If international cooperation were involved in developing such specifications, pesticide manufacturers would rapidly respond to this market. This would result in selective chemicals at the lowest cost.

Biological agents

Indigenous and introduced biological agents for mosquito control need to be considered. However, importing, mass-producing, and releasing given biological agents into ricefields is impractical, even in small-scale rice production systems. Biological organisms, which through millions of years of natural selection come to occupy small niches in the ecosystem, are unlikely to be operationally useful.

A good example of this is the nematode *Romanomermis culicivorax,* which has been evaluated in numerous trials against mosquitoes. Westerdahl et al (1982) released post-parasites of this nematode into ricefields and found that infection of mosquito larvae occurred throughout a rice season. Infections, however, were limited to within 12 m of a single release point. Although recycling occurs, the inability of the nematode population to spread from release points renders this approach impractical.

The use of mosquito fish *Gambusia affinis* has been effective against the mosquito *Culex tarsalis* in California ricefields, but its effectiveness against *Anopheles* spp. is questionable (Hoy et al 1971). Another problem with *G. affinis* is that it preys on eggs of other fish; therefore, its introduction might reduce indigenous fish species.

The use of *G. affinis* and *Poecilia reticulata* for controlling mosquito larvae in various habitats has long been attempted. Research is needed to identify indigenous fish species more suitable to the ricefields of individual developing countries. A promising concept is that of enticing local rice farmers to stock their fields with larvivorous fish that could later be harvested for food. However, the fish most likely to be successful in given sites and the means of providing them in sufficient numbers need to be determined.

Probably, the least attention to date has been given to indigenous insect predators. Their taxonomy and ecology need to be studied before their efficacy can be determined and ways of multiplying them evaluated. Numerous aquatic predator species occur in most ricefields, but their potential for mosquito control is unknown in most parts of the world. These organisms must be studied so that their possible use in integrated control can be assessed.

Physical approaches

Intermittent irrigation may be used where water is plentiful. However, several problems should be addressed. For example, flushing fields may simply move mosquito populations downstream; and mosquito populations can quickly build up in scattered puddles, which remain after draining and are often devoid of predators (Schaefer et al 1982). Irrigation ditches should be drained when they are not in use because standing water in ditches and other adjacent lands can result in major mosquito breeding. Engineering designs to avoid this problem frequently are not included in ricefield planning and construction.

Key problems in initiating integrated mosquito control

We must not continue to approach mosquito control as a separate discipline. We must work closely with those involved in planning and implementing rice production strategies. This will be difficult, because the persons involved are usually in different bureaucracies.

If we are to cope with insect vectors of disease, we must understand the taxonomy and ecology of each vector species. Integrated control requires the same biological information on various aquatic organisms that coexist in the ricefield habitat. That will require adequate numbers of persons trained in aquatic biology.

We must develop operationally acceptable means for surveying and monitoring populations of both target and key nontarget organisms. Using these methods, we must also define population densities or thresholds of target species that can or should be tolerated. These thresholds may vary by situation encountered. For example, the threshold for vectors in small-scale rice production systems may be lower than for large systems because of the proximity of people to the small systems.

Also, we need to develop criteria for relating the trends of predator populations to the need of chemical control. Those criteria must be easily understood by persons in small-scale rice production systems.

Finally, we must continue to emphasize the need for commercially available selective chemical control agents. When population densities of a pest or vector exceed the defined tolerance threshold, it is essential to have chemical agents available that will do the least harm to the nontarget complex.

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Authors' addresses: C. H. Schaefer, Mosquito Control Research Laboratory, University of California, 9420 S. Riverbend Ave., Parlier, California, 93648, USA; and M. V. Meisch, Department of Entomology, University of Arkansas, Fayetteville, Arkansas, 72701, USA.

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Control of *Schistosoma japonicum* snail intermediate host in riceland agroecosystems

E. G. GARCIA

The snail host of the geographic strains of *Schistosoma japonicum* endemic in China, Philippines, Japan, and Sulawesi in Indonesia are subspecies of *Oncomelania hupensis,* an amphibian, operculated snail that is strictly aquatic during its first 2 wk of life. Based on the bionomics of *Oncomelania,* environmental control methods that alter the snail habitat have effectively controlled or even eradicated this snail in Japan, in extensive riceland areas in China (excluding Taiwan Province), and in limited areas in the Philippines. These methods include removing water by drainage and proper irrigation water management, removing shade or shelter by clearing vegetation from stream banks or irrigation channels, preventing breeding by lining stream banks and irrigation channels with concrete or making the sides more nearly perpendicular, and accelerating water flow by proper gradient and removing debris. When properly maintained, these alterations lead to snail eradication. Intensive riceland cultivation, with proper seedling spacing, weeding, and water management, has led to snail control in ricefields. That, coupled with snail control in irrigation channels by environmental alterations, controls *Oncomelania* snails in riceland ecosystems.

Schistosoma japonicum is endemic in tropical and subtropical Southeast Asia following the distribution of freshwater *Oncomelania* snails. China has the largest endemic areas, with 10 million persons estimated to be infected. These areas include the marshes and lowlands in the region of Taiku, Poyang, and Tongtin lakes; areas on the Yangtze River basin and delta; and some southern provinces bordering the upper Mekong River. A nonhuman strain of *S. japonicum* is endemic in Taiwan, China.

In the Philippines, 6 of the 13 main islands are endemic, with 700,000 persons estimated to be infected. These areas are Irosin valley in Sorsogon Province, Luzon; Samar; northeastern Leyte; Bohol; around Lake Naujan in Mindoro; and Mindanao. Lake Lindu and the Napu valley in Central Sulawesi are the endemic areas in Indonesia, with not more than 20,000 persons estimated to be infected. *S. japonicum* used to be endemic in Honshu and Okayama islands in Japan, but may now be considered as eradicated.

S. mekongi, a *S. japonicum*-like parasite, has been reported in Khong Island in Laos and in Kratze in Cambodia in the Mekong delta, with *Tricula aperta* as the snail host.

The snail intermediate hosts of *S. japonicum* are gastropods belonging to the family Pomatiopsidae, subfamily Pomatiopsinae and are contained in the genus *Oncomelania* as subspecies of *Oncomelania hupensis* (Gradler). They are: *O. hupensis* ssp. *hupensis* (Gradler) on the mainland of China, *O. hupensis* ssp, *formosana* (Philsby and Hirase) and *O. hupensis* ssp. *chiu* (Habe and Miyazake) in Taiwan, China; *O. hupensis* ssp. *nosophora* (Robson) in Japan; *O. hupensis* ssp. *quadrasi* (Mollendorf) in the Philippines; and *O. hupensis* ssp. *lindoensis* (Davis and Carney) in Sulawesi, Indonesia. The main differences between each subspecies are shell size, sculpture, electrophoretic and antigenic differences, and differences in susceptibility to different strains of *S. japonicum.*

All of these snails are operculated, amphibious, and dioecious. To a great extent, their ecologic requirements are qualitatively similar but quantitatively different. Although they are most often found near sea level, they are found at higher elevations as well. At whatever elevation, the topography of the snail-inhabited areas is level. This topographic feature promotes the retention of water (a point of obvious importance to an animal with an aquatic stage in its life history) and makes the land suitable for lowland rice cultivation.

Biology of *S. japonicum*

Transmission of *S. japonicum* requires contact with water harboring infected *Oncomelania* snails in an area where sanitation is not satisfactory and there are infected persons and animals. Many animal reservoirs of *S. japonicum* have been identified. Although their relative importance in transmission in most endemic areas has not been evaluated, it is reasonable to presume that in the absence of human infection, animals can maintain the parasite's life cycle at a measurable level. In China, at least 31 wild mammals and 13 domestic animals have been found naturally infected. In the Philippines, domestic mammals, wild rats, and monkeys have been found infected. Similarly, domestic and wild animals have been found infected in Sulawesi.

In an endemic community in the Philippines, the dog, cow, pig, rat, carabao (water buffalo), and goat (in decreasing order of importance) were considered responsible for about 25% of the total environmental contamination with eggs in fecal materials—humans contributed the rest. This estimate was based on the total animal population, prevalence, mean daily egg-output, and hatchability. The epidemiologic situation will vary in other areas depending on the proportion of human to animal populations.

Male and female *S. japonicum, in copula,* inhabit the branches of the portal venous system, which drains the blood from the intestines. The worms do not multiply in the mammalian host. The eggs they lay must be excreted to reach the snail intermediate host and develop into an infective stage (for mammalian hosts). Eggs are laid in terminal veins of the portal system and contiguous capillaries of the tissue and mature in 8-10 d with the development of a larval stage called the miracidium. Eggs deposited in the superficial layers or mucosa and submucosa of the intestines reach the lumen through ulcerations and are excreted with the feces. *S. japonicum* eggs deposited on shaded ground can survive for more than 1 wk.

In fresh water the mature egg hatches with the liberation of a free-swimming embryo, the miracidium. The miracidium penetrates the *Oncomelania* snail and develops into a mother sporocyst, which in turn produces many secondary sporocysts where cercariae, the infective stage for the mammalian host, are formed. The cercariae leave the snail and swim on the surface water where they can survive for as long as 48 h. From penetration of miracidium to first shedding of cercariae by the snail, the average period is 62 d with the Philippine strain. The cercaria shedding period may last for 2 mo. Experiments, also with the Philippine strain, indicate that from a single miracidium only relatively few or several cercariae are shed daily. However, the snails may be stranded for several days on vegetation above the water or in the moist soil, and on reentry into the water will shed more cercariae. In general, there is no difference in the susceptibility of either sex of *Oncomelania* to infection with *S. japonicum,* although survival of infected snails is reduced.

The usual mode of infection of mammalian hosts is by penetration of cercariae through the skin while it is in contact with water. The cercaria is transformed into a schistosomule (larva) after skin penetration. The larvae migrate through the circulatory system to the lungs and finally to branches of the portal vein where they mature. With the Philippine strain, egg deposition starts as early as 25 d after skin penetration or infection. A single female can lay 1,000–1,500 eggs/day. Although infected individuals, who have been away from endemic areas for 20 yr, have been found passing viable eggs, it is generally calculated that the average life of *S. japonicum* is between 3 and 6 yr.

Biology of *Oncomelania* snails

The *O. hupensis* ssp. *quadrasi* adult snail measures 3.5 mm; the adult (*O. hupensis* ssp. *hupensis*) measures 9.5 mm. The shell is smooth, dextral, conical or subconical, with four to eight whorls with a calcareous operculum. The operculum enables *Oncomelania* snails to survive for more than a week without water.

A number of descriptions of the habitats of the snail intermediate host of the different strains of *S. japonicum* appear in the literature. These include floodplain forests, swamps, waterlogged grasslands, small streams, ricefields, irrigation canals, road ditches, and borrow pits. They are seldom found in large rivers and fast-flowing streams. A common feature of these areas is that they are level, never dry out for a significant period, and always have some vegetative cover. Snail colonies are more or less permanent unless they are disturbed or their habitat is altered.

The distribution of these amphibious snails in water and soil portion of their habitats is neither even or random but clumped. In a stream or small swamp, they are found in the water, on the banks, and in the adjacent area up to the point where the soil is moist and covered with vegetation. In the water, they are more numerous in the shallows, in the stream bed, or they may be perched on protruding rocks or floating leaves or branches.

O. hupensis ssp. *quadrasi* can easily survive up to 200 d. Other species have been reported to survive longer. They are presumed to survive on some species of algae and diatoms. In the laboratory they can survive on decaying leaves. *O. hupensis* ssp. *quadrasi* start egg laying by the age of 90–100d or by the time they reach 3.5 mm in size. A single copulation will enable a female to lay eggs for several days. An average of 2 eggs are laid every 5 d. Eggs are laid on sloping banks of streams at the interface between soil and water and on rocks, twigs, or leaves on the water surface, but not on steep banks of water courses. *Oncomelania* snails are strictly aquatic during their first 2 or 3 wk of life. They repopulate rapidly. It is calculated that if only 16% of eggs survive to maturity, there would be 4.4 adults in the next generation for each female adult snail.

Ricefields as snail habitats

The association of Asian schistosomiasis with rice-growing areas has been reported by different authors. Several workers, based on observations in Japan shortly after World War II, recorded that ricefields themselves did not seem to be habitats (no evidence of breeding), but snails found in the ricefields appeared to have spread or washed from irrigation canals or from adjacent snail infested fields. Others have reported large populations of breeding snails in ricefields. These contrasting observations are a function of how recently the snail habitat has been utilized for rice cultivation, and the intensity, continuity, and method of rice culture practiced before the investigator has seen the field.

Floodplain forests, swamps, waterlogged grassland, and lakeshores probably represent the original snail habitats that have been turned into ricefields. During 1952, a schistosomiasis control unit of the Philippine Ministry of Health stationed in Malaybalay, Bukidnon Province reported the presence of snails in all ricefields in the village of Managok, Malaybalay. In September 1955, another survey revealed that snails remained in only 1 field that had been abandoned for 2 yr and were abundant in adjacent ditches. In the endemic area in the Philippines where the ricefields are intensively cultivated with at least two crops a year, snails are found only in adjacent ditches or canals. In areas where fields are idle part of the year and rice cultivation is less intensive, snails breed in the field.

For snail control, it is important that irrigation and drainage channels adjacent to or traversing ricefields be considered part of the riceland agroecosystem. It is doubtful that farmers become infected during land preparation, weeding, or harvest. More farmers probably become infected while washing their muddied legs in the irrigation channels.

Control of *Oncomelania* snails

The present emphasis on chemotherapy in schistosomiasis control must not be misinterpreted to mean that there is no place for snail control in the overall strategy. *S. japonicum* has a wide range of mammalian hosts and community-based chemotherapy alone is unlikely to be satisfactory in controlling transmission.

Control of the snail intermediate host is an effective means of reducing or stopping transmission of schistosomiasis. Its efficiency is enhanced when combined with other measures. Environmental, chemical, and biological methods can be applied to snail control in the riceland agroecosystems.

Environmental and habitat alteration

Environmental control involves altering the habitat to make it unacceptable to the snail and to prevent breeding. The more radical the alteration, the more profound is the effect on the snail population. Based on *Oncomelania* environmental requirements, environmental control would include water drainage and proper water management; clearing of vegetation; liming the banks of canals with concrete or making the bank steeper; and grading and cleaning of the stream bed to accelerate the water flow. The effectiveness of such alterations, which are not permanent, should be made lasting with proper maintenance. It can readily be seen that these are easily applicable to the irrigation systems of the riceland agroecosystem. Although snail control can be done on a focal basis, it should be done on the whole watershed whenever possible.

In Japan, *S. japonicum* eradication was accomplished by treatment, sanitation, control of animal reservoir hosts, education, and eradication of most of the snail colonies. Irrigation channels were lined with concrete and maintained clear of silt, vegetation, and debris to supplement the eradication of snails in the ricefields proper, which resulted from intensive cultivation. Land was reclaimed by drainage and filling. These measures were supplemented by mollusciciding. Socioeconomic factors including better education, better housing, and industrialization (including discharge of toxic wastes into water courses) also must have contributed to eradication of *S. japonicum* in Japan.

Extensive rice-growing areas in China's mainland have been cleared of *Oncomelania* snails. The measures included digging new water channels parallel to the existing snail-infested streams and using the excavated soil to fill the old ones; clearing stream beds, and removing vegetation. Where the soil structure permitted, the banks were made steeper. The lake regions remain the problem areas in China because of the magnitude of the engineering and resource requirements.

In the Philippines, reclamation by filling or covering snail habitats with soil; steepening the banks; clearing vegetation; drainage; converting undrainable, swampy areas into fishponds; and improving agricultural practices, particularly rice cultivation, have successfully controlled snails in limited areas.

One of the constraints to environmental modification of habitat is the cost. Japan was able to afford the large capital expenditures for lining canals, reclaiming swamps, and sustaining the control program. In China, the sociopolitical structure made it possible to implement the necessary environmental changes without resorting to large capital expenditure. In other parts of Asia, where money is scarce, increased community participation is needed to insure the success of control programs.

Snail control by environmental methods has several advantages: 1. It can be integrated into regional agricultural and other rural developmental projects. 2. The results can be made permanent by regular maintenance. 3. Increased agricultural productivity results. 4. Control measures can be done locally by the people themselves. 5. Land value increases, and 6. No foreign exchange is required.

Rice cultivation is an environmental method of snail control in that it brings about ecologic changes, which eventually reduce snail habitats. Based on experiments utilizing different methods of rice culture, the Philippines is promoting more intensive and more scientific methods of rice cultivation to control schistosomiasis. Snail control is achieved at different stages of rice growing in the following manner:

1. Deep plowing turns over the soil and buries the snails.
2. Harrowing removes weeds that may provide shade for snails while the rice is growing and contributes to the burial of snails.
3. Proper spacing of the rice seedlings exposes snails to sunlight during part of the rice growing season.
4. Weeding diminishes vegetation canopy and may bury some snails between the rice seedlings.
5. Insecticide or pesticide to protect the rice crop may be molluscicidal.
6. Draining the ricefield at harvest and keeping it dry until the next crop kills the snails and prevents breeding.
7. Drainage at the terminal point of the irrigation system prevents that area from being continuously waterlogged and becoming a transmission site.

Biological control

Biological control uses organisms to attack the snails or sterilization of males to prevent reproduction. The reduction of snail population by introducing sterile males, however, has not shown promise. Similarly, the use of some fish and ducks as predators has been unsuccessful. Much more research is needed. Researchers are attempting to identify bacteria or fungi that are pathogenic to *Oncomelania.*

Chemical control

A large number of chemicals have been screened for molluscicidal activity against *Oncomelania.* Two, sodium pentachlorophenate and niclosamide, have been used, principally on a local basis. Crude extracts of plants of the genus *Entada* and *Jatropha curas* have been tried in the Philippines, but they have severe limitations.

The amphibious nature of *Oncomelania* snails requires application of the molluscicide to adjacent moist areas in addition to direct application to the water. The terrestrial portion of the habitat and banks of irrigation canals are frequently overgrown by vegetation and aquatic plants have portions that extend above the water level. That vegetative cover may prevent the molluscicide from reaching the snails even if it is applied to the water and adjacent moist areas. Consequently, removing vegetation and debris from the habitat is required before mollusciciding.

Moreover, the operculum protects the snails from the molluscicide and *Oncomelania* can reproduce rapidly. That, and the high cost of mollusciciding, makes chemical control suitable only for seasonal control in small transmission sites. Molluscicides are best applied as a terminal treatment after environmental alterations have had their full effect.

Research needs

It is apparent from the experiences in Japan, China, and the Philippines that *Oncomelania* snails can be controlled or even eradicated by environmental alterations, which may or may not require terminal mollusciciding. Therefore it is important that environmental alterations of snail habitats be made part of rice growing practices and that more cost-efficient methods be developed. For example, cheaper methods and materials for lining irrigation channels should be developed. Additionally, health education for inhabitants of the riceland agroecosystem is necessary.

During the past years molluscicides have been undesirable because of their wide spectrum of activity, including detrimental effects on desirable species such as fish, their accumulation in the environment, and their increasing cost. It is important to concentrate on the development of biological control methods to supplement environmental methods. More effort must be made to identify bacteria, fungi, or protozoa that are pathogenic to *Oncomelania.*

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Author's address: E. G. Garcia, Institute of Public Health, University of the Philippines, 625 Pedro Gil, Ermita, Manila, Philippines.

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Control of the *Schistosoma mansoni* and *S. haematobium* intermediate hosts in ricefields

A. A. El Gaddal

Good water supply and sanitation combined with health education can help to prevent human-pathogen contact in irrigation and drainage canals. Water contact in irrigated ricefields, however, cannot be avoided so easily. Special measures are needed to prevent the invasion of the ricefields by the snail intermediate hosts of the schistosomiasis. Four accepted methods of snail control are discussed. Biological control using snail species that compete with or prey upon intermediate host species is promising. The snail *Marisa cornuarietis,* however, is not a feasible biocontrol agent in ricefields because it feeds on rice seedlings. Interest in natural molluscicides extracted from plants has waned and of the chemical molluscicides only niclosamide is still widely used. Environmental manipulation relies heavily on weed control in canals; aquatic weeds provide habitat and food for snails. Engineering methods, such as the use of meshed siphons, are also important. Finally, the importance of accompanying any control activity aimed at the snail intermediate host with chemotherapy is pointed out. Highly effective and relatively inexpensive drugs are now available, but are useful only when water supply, sanitation, and environment are managed to prevent reinfection. Examples are given from Kenya and Tanzania, where these four measures have been successful to some extent.

Schistosomiasis is probably the second most feared and widespread disease in Africa after malaria. It is one of the few diseases in Africa that are being spread by the current push toward development through increased food production, which involves greater use of water resources and construction of dams for irrigation schemes.

Water development projects in general may give rise to epidemics of vector-borne diseases, of which schistosomiasis is almost certain to be one, and rice schemes are no exception. With the expansion of the area under rice cultivation in Africa, it is time to consider the likely consequences of increased transmission of schistosomiasis, and to draw attention to the need for effective controls.

Rice cultivation itself does not always lead directly to increased schistosomiasis. In the Ahero project in Kenya, snails were prevented from becoming established through collaboration between the Ministries of Health and of Irrigation. This action was prompted by the initial disastrous rise in schistosomiasis prevalence in an earlier scheme at Mwea/Tabere in Kenya.

In Tanzania, Sturrock (1965) found rudimentary but effective control of schistosomiasis transmission in ricefields in the 40-ha Baluchi Irrigation scheme. There were few snails in the canal system itself because of two factors. First, the water flow was relatively fast. Second, the canals were cleared of silt and vegetation twice yearly. In the ricefields, the irrigation system allowed the fields to be plowed, manured, and alternately dried and flooded. Consequently, neither the canals nor the fields offered the snails any permanent habitat for colonization. One other point is that there is no resident human population within the irrigated area.

The intermediate hosts of schistosomiasis are sensitive to the microhabitat within a larger aquatic environment. Changes in pH, water velocity, temperature, sunlight, aquatic vegetation, and other parameters can render a microhabitat particularly suitable or unsuitable for breeding of snails. Within an irrigation system, the parent canals and reservoirs are likely to be particularly suitable for snails, but water contact in these bodies may be controllable. The ricefields, however, are sites in which water contact just cannot be avoided, and therefore the fields present extremely dangerous potential transmission sites. However, because of the type of habitat, it is usually possible to make the ricefields a particularly unsuitable microhabitat for the colonization by intermediate host snails. High temperatures and periodic drying of the habitat are the two factors most likely to make the fields unsuitable.

All field biologists recognize that the distribution of snails within a water system is always patchy and the snails clump together in some places while they are absent from other stretches of shoreline. The combination of chemical, physical, and biological factors, which different snails find to their liking, has never been defined for any species, although guidelines do exist as a result of the extensive chemical work carried out in laboratory studies by Dr. J. D. Thomas and his group at Sussex University in the United Kingdom.

To initiate environmental management that will adversely affect the snail populations, the fullest understanding of the biology and ecology of the vector, the snail population dynamics, and the disease epidemiology is essential. To interrupt the life cycle of schistosomiasis in ricefields, it is essential to eliminate infected snails or eliminate contamination of the water by infected fecal and urine excretions.

Snail control

The accepted methods of snail control are biological control using predator or competitor species, plant molluscicides, and environmental management.

The only biological control method that has shown positive result is the use of predator and competitor snail species to supplant the vector species. The species that have been reported to have successfully replaced schistosome vector snails in the field are *Marisa cornuarietis* and *Thiara.*

Marisa cornuarietis is a huge ampullarid (compared with its *Biomphalaria* target snail), which has been used successfully in Puerto Rico in large ponds as a competitive feeder and incidental predator on *Biomphalaria glabrata.* A recent report suggests that *Marisa* has replaced *B. pfeifferi* in an aquatic habitat in

Tanzania. At present this snail is undergoing extensive field trials in the canals of the Gezira scheme, where it has successfully survived more than 18 mo. In two canals it has bred successfully, and apparently has taken over from the vector snails in about two-thirds of the canal.

At this point it is important to mention that the snail *M. cornuarietis* has been reported to be such a voracious eater of young vegetation that it is thought that it may destroy young rice seedlings if it were ever allowed to colonize a field of newly transplanted rice.

The snail *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 Africa field situations is *Helisoma duryi* which may use a combination of competition and growth-inhibiting factors to replace snails in freshwater habitats.

In the 1970s it was thought that plant molluscicides could be the answer to snail control and that Third World 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.

Over a 50-yr period a number of chemical molluscicides have been used extensively to control vector snails in all types of habitats from stagnant pools to large-scale irrigation networks. They have been applied with the aim of eradicating snails or the more modest aim to control only infected snails in transmission foci. By 1987, the shortcomings of most candidate molluscicides had been exposed, and they have fallen from use. Only one commercially available chemical remains (niclosamide) and it is generally applied in regular focal treatment of known transmission foci.

The major disadvantages of niclosamide are that it is relatively expensive and must be used indefinitely. It is toxic to fish and can cause some damage to aquatic vegetation. Also, snail control is aimed only at transmission. Therefore the use of molluscicides in an area in which schistosomiasis prevalence is already high is useless unless combined with mass chemotherapy.

On the other hand, the use of a chemical molluscicide is usually easy to organize and does not require the cooperation of the general public to achieve the target of reducing the infected snail population. In areas where there is a high potential for transmission in limited bodies of water, then this technique offers an excellent chance of economical control.

In the Mwea/Tabere rice scheme in Kenya, niclosamide was eventually resorted to and the chemical is now applied six times a year to the canals and drainage system. When it was applied only to the canals, the chemical did not penetrate to the drains and a separate treatment schedule was necessary for the drainage system. Since the enlarged regimen was introduced, it is thought that transmission has been controlled (Choudhry 1974).

Most snails feed on vegetation and there is a direct correlation between snail populations and the density of aquatic vegetation. Therefore it is essential to keep feeder canals free of weeds to prevent explosive growth in snail populations. The weed provides not only food for the snails but an egg-laying surface and cover for the hatchlings. This was particularly noticed in the Yagoua rice scheme in Northern Cameroon (Wilbaux-Charlois et al 1982). On the same scheme the prevalence of *Schistosoma haematobium* was directly proportional to the proximity of dwellings to the nearest canals. This phenomenon has been demonstrated clearly with respect to *S. mansoni* prevalence in the Gezira scheme.

On Zanzibar, 5 pilot sites totaling some 560 ha have been given over to rice cultivation. Zanzibar is known as endemic for *S. haematobium* with a prevalence of about 30%. Therefore the risk attached to irrigated rice cultivation is obvious. It has been suggested that the best way to prevent increasing schistosomiasis would be to use siphons to transport the water, and to screen the siphons with mesh to prevent the snails from invading the fields.

At the same time, human-water contact would be minimized by providing pumped clean water for domestic use (Pozzi 1986).

On the Gorgal scheme in Mauritania, Jobin (1978) predicted that snails would not establish themselves in the ricefields, but would be a problem only in the canals and the drainage system. The designers arranged that all fields would be completely dried twice a year, and Jobin believed this would be sufficient to control any snails within the fields themselves. To complete control on the Gorgal scheme, it was suggested that the perennial water contact sites of both the main canal and the River Gorgal should be fenced off to prevent extensive human-water contact and transmission (Dalton 1976).

In the rice schemes of Burkina Faso, schistosomiasis prevalence has been reportedly reduced as a result of legislation requiring health education and the improvement of sanitation.

Improved water supplies and sanitation

Environmental methods have been used to reduce the prevalence of schistosomiasis in a number of areas with various success. They include improving the socio-economic conditions of the people, providing water supplies and sanitation facilities, and imparting health education.

On the West Indies Island of St. Lucia, the research and control project against schistosomiasis showed, for the first time, the value of providing water for washing and showering and piped clean water to improve the quality of life while significantly reducing the human-water contact that leads directly to schistosomiasis (Jordan 1985).

Many other schistosomiasis control projects have since paid special attention to the engineering side of reducing man’s dependency on raw water, and in improving sanitation and health education. The Lake Volta Project and the Blue Nile Health Project are two examples of this increased realization of the value of pure water in the fight against schistosomiasis.

The value of chemotherapy against schistosomiasis is immense. Chemotherapy is an essential element in every control program, but is much better if used in conjunction with other control approaches. In Gezira we do not implement our mass chemotherapy program until the water engineers have installed new water supplies or rehabilitated existing ones. Sanitation is a much more difficult input, but again we make a start on improving latrines before implementing a mass chemotherapy campaign in any village.

The inescapable conclusion from a review of the sparse literature and experience on the control of schistosomiasis vectors in ricefields is that the problem is greater than it ought to be merely because there has not been the will to control the vectors. The fields themselves should not really be a large problem in most areas. Snail control in ricefields should be possible with cooperation between biologists and engineers at an early stage of scheme construction. Fields can be managed so they are unsuitable for snails, pure water and sanitation can be provided for the inhabitants, and villages can be sited away from potentially dangerous water bodies.

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Author's Address: The Blue Nile Health Project, P.O. Box 101, Wad Medani. Sudan.

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A malaria epidemic caused by *Anopheles ludlowi* in East Java in 1933

W. B. Snellen

The outbreak of malaria in a village on the northern coast of Java, Indonesia, in 1933 was attributed to the formation of brackish pools in saline ricefields, which had not been planted because of abnormally low rainfall. In contrast to the normal practice of identifying breeding sites through larvae finds, meteorological and soil data are used to indicate where and when a combination of environmental factors favorable for vector breeding occurs. A theoretical vector density curve derived from the ponding curve in the saline ricefields appears to correspond with the mortality curve 35 d later. This was considered evidence that breeding of *Anopheles ludlowi* in the saline ricefields caused the epidemic.

This paper summarizes a description of a malaria epidemic that occurred in East Java, Indonesia, in 1933 (Kuipers and Stoker 1934). The paper is noteworthy in that it related information on the breeding habits of the vector with meteorological and other readily available technical data to predict not only where but when a specific area would likely favor vector breeding and pose the risk of an epidemic.

Based on that model, the authors suggested that by predicting the conditions that favored vector breeding, sanitation workers could intervene beforehand. In the discussion, I raise the question whether the direction taken by Kuipers and Stoker more than half century ago is still relevant today.

Medical description

W. J. Stoker, government physician for the Malaria Control Office in Surabaya, described the medical aspects of the epidemic.

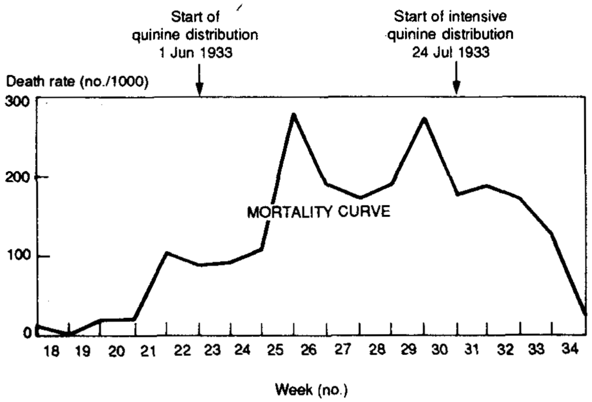
A severe malaria epidemic occurred in the village of Brengkok (5,714 inhabitants) on the northern coast of East Java from June to August 1933. The increase in the mortality rate—from the normally accepted 20/ thousand in wk 17-20 to 100/thousand in wk 21—drew the attention of the Provincial Health Service.

A government-appointed assistant physician was sent to collect blood samples from patients. When it appeared that each sample contained malaria parasites (mostly malaria *tropica*), a sufficient quantity of quinine was immediately supplied for distribution by the village council.

Despite the quinine treatment, the mortality rate remained high (Fig. 1). Investigations by the Provincial Health Service seemed to indicate that the drugs had not been properly distributed by the village council. (No further details are given.) To ensure a systematic distribution of quinine, a technical assistant from the Malaria Control Department was sent to Brengkok. He stayed there from 24 July to 24 August. On 24 July, a government physician and the technical assistant conducted a medical survey of the village population. They made spleen examinations and ran blood tests, not specifically among the sick, but from a random group of people who attended a meeting at the home of the village head. Table 1 summarizes the results of the survey. The figures reveal the symptoms in the population that are typical during an acute malaria epidemic.

- The spleen index is much lower than the parasite index.
- None of the persons examined had a highly enlarged spleen.
- The infection index is higher than the parasite index.

The interpretation of the data from the medical survey agreed with information that had been received from the civil administration and the local villagers, who claimed that both the disease and the high rate of mortality were unusual in



1. Mortality curve during a malaria epidemic in the village of Brengkok, East Java, Indonesia, in the 1933 wet season.

Table 1. Results of initial medical survey of the population of Brengkok, East Java, Dutch East Indies, 24 Jul 1933.

Sex[a]	Examined (no.)	Splenic enlargement class					Mean spleen index (%)	Parasite index (%)	Infection index (%)
		I	II	III	IV	V$^+$			
Child < 6	37	14	2	1	1	–	49	92	127
Child > 6	87	22	13	1	–	–	41	77	103
Female	89	25	9	2	–	–	40	74	82
Male	85	21	8	2	–	–	39	80	102

[a] Children not differentiated by sex.

Table 2. Results of *Anopheline* mosquito collection and dissection in Brengkok. East Java, Dutch East India, July-August 1933.

	Anophelines collected (no.)			Anophelines infected (no.)			
	From cowshed in 1 night	From houses (24 Jul-21 Aug)	Total	Anophelines dissected (no.)	Stomach	Salivary gland	Total
A. subpictus	43	971	1014	964	–	–	–
A. ludlowi	–	157	157	146	44	36	68
A. aconitus	1	1	2	2	–	–	–

Brengkok. They mentioned, however, that malaria did occur regularly in the nearby village of Manjaroeti, 2 km west of Brengkok.

The technical assistant from the Malaria Control Department also collected and dissected anopheline mosquitoes.

The results of his examinations (Table 2) clearly indicate that the epidemic was caused by *Anopheles ludlowi* var. *sundaica.*

A. ludlowi breeds in sunlit, brackish pools. Figure 2 shows four zones around Brengkok where such breeding sites might occur:

1. the marine fishponds, extending from Brengkok to the coast,
2. the wasteland between the fishponds and the village,
3. the transition zone between the fishponds and the traditional riceland, and
4. the saline riceland.

After investigation of these zones, the authors concluded that the 1933 epidemic was attributable to the formation of brackish pools in the saline riceland (zone 4), which had not been planted because of the abnormally low rainfall during the land preparation period. How the authors arrived at this conclusion—and stuck to it, even though the larvae they found in the remaining pools produced only *A. subpictus*—is explained by J. Kuipers, chief engineer, Provincial Sanitation Office, East Java.

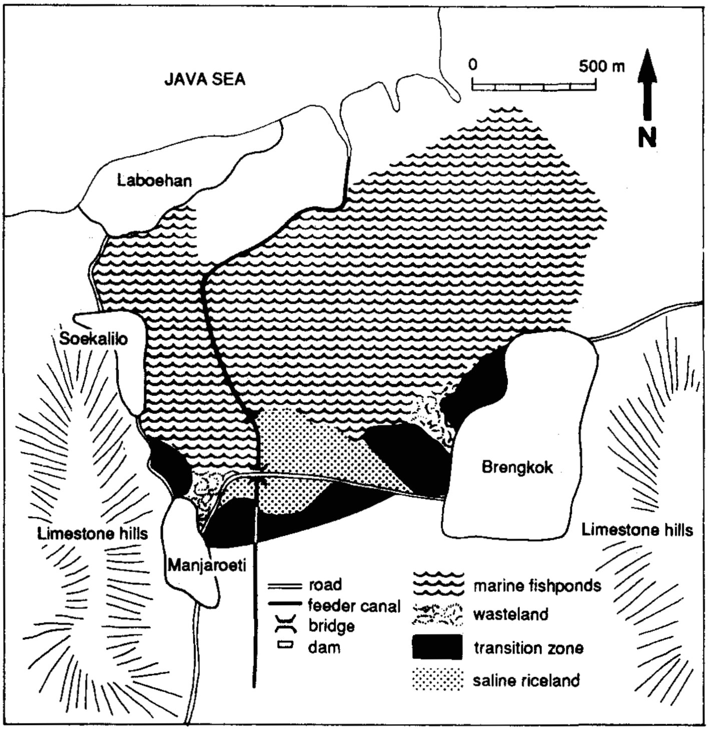
Technical description

Kuipers first considered the potential danger of each of the four zones:

Marine fishponds

The marine fishponds were regarded as safe because of a process known as hygienic exploitation. Marine fishponds were notorious breeding sites for *A. ludlowi* and were considered the major contributor to coastal malaria. Large sums were spent to fill fishponds and the *Guidelines for malaria control for government officials,* issued in 1924, warned strongly against creating new fishponds in the coastal area.

Later, it was discovered that fishponds kept clean of floating algae were perfectly safe. Floating algae were prevented by periodically draining the ponds, which was called hygienic exploitation.



2. Potential breeding sites for *A. ludlowi* near the village of Brengkok, East Java, Indonesia, 1933.

Wasteland

Between the village and the fishponds was an uncultivated area of 2 ha, with an irregular surface and saline groundwater. In the rainy season, the water table would rise, filling small depressions and holes with brackish water. Although these sites were potentially dangerous, the author considered their collective surface area too small to sustain a heavy malaria epidemic.

Transition zone

Between the marine fishponds and the traditional riceland was a transition zone that was subject to periodic flooding with brackish water from the fishponds. The zone consisted of uncultivated land and some ricefields near the village of Manjaroeti that were irrigated from a small reservoir. Because of the high salt content of the soil, irrigation water or rainfall that remained in the field gradually became brackish. The irrigated ricefields themselves were not particularly dangerous because *A. ludlowi* does not breed in water shaded by rice plants.

A greater danger was the surface runoff, or excess irrigation water, from the ricefields, which, in combination with imperfect drainage of the adjacent uncultivated land, might create sunlit pools with brackish water. This explained the regular occurrence of malaria in Manjaroeti. Kuipers proposed improving the drainage of the zone by deepening the main ditch and lowering the water level in the feeder canal upstream from the dam (Fig. 2).

Saline riceland

The traditional rice-growing area lay between the transition zone and the limestone hills. Rice cultivation depended on rainfall alone. (Apparently, the high permeability of the limestone hills prevented the occurrence of small streams that could be used for irrigation.) The ricefields close to Brengkok were highly saline because of inundation by seawater long ago. The high salinity of these fields, despite their having been used as ricefields for as long as could be remembered, was explained by the very low permeability of the heavy clay soil.

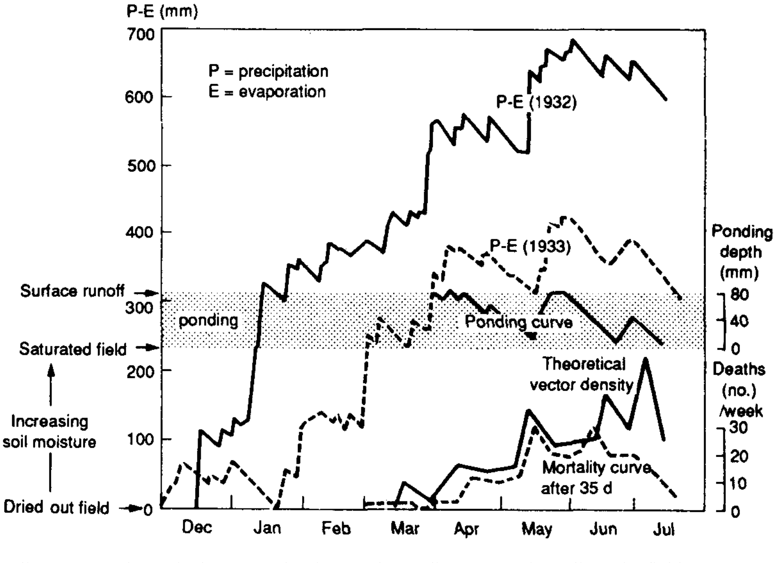
Water that remains on a saline ricefield will become brackish after a time. But with adequate rainfall, two factors will reduce the chances of these ricefields becoming breeding sites for *A. ludlowi.*

1. *A. ludlowi* is a sun-loving species, and will not breed in a field planted to rice.
2. The time between two subsequent rainstorms is usually sufficiently short to prevent the water in the field from becoming brackish. With each rainstorm, the water in the field is replaced by or diluted with fresh water.

Nevertheless, these two factors did not come into play in 1933 for the following reasons.

- Because of insufficient rainfall in December and January, the ricefields could not be prepared in time for planting. As a result, most of them remained uncultivated.
- From March on, ponding occurred in the uncultivated ricefields. The lower and less frequent rainfall than usual allowed the ponds to become brackish.

Because of the abnormal rainfall pattern in 1933, the brackish ponds that developed on the saline, uncultivated ricefields became excellent breeding sites for *A. ludlowi.* Kuipers used meteorological data (rainfall and evaporation) and soil characteristics (soil moisture retention) to produce a ponding curve (Fig. 3). From



3. Mortality curve, theoretical vector density, and ponding curve in saline ricefields near Brengkok, East Java, Indonesia. Curves were derived from rainfall, evaporation, and soil data, the ponding curve, he derived acurve representing the theoretical vector density. The shape of his vector density curve very much resembles the mortality curve of 35 d later.

Although Kuipers went to a lot of trouble to explain how he derived the vector density curve from the ponding curve, I have not reproduced his explanation in the interest of brevity. I have not reproduced his discussion for two other reasons. First, I have a feeling that Kuipers was rather too resourceful in obtaining a vector density curve that perfectly matched the mortality curve. Second, I think we do not need the vector density curve at all to appreciate the relation between the ponding curve and the mortality curve of 35 d later.

Kuipers explained the time lag of 35 d between the vector density curve and the mortality curve as follows:

Day 0	*A. ludlowi* mosquito emerges.
Day 1	*A. ludlowi* has its first blood meal and becomes infected.
Day 14–16	The infected *A. ludlowi* bites another person.
Day 21–30	The victim develops the first symptoms of malaria.
Day 27–40	The victim dies. (An average of 35 days has elapsed since the emergence of *A. ludlowi*.)

The authors considered the resemblance between the vector density curve, which is derived from the ponding curve of the saline ricefields, as evidence that the epidemic was caused by prolific breeding of *A. ludlowi* in the uncultivated ricelands in that zone.

To remedy the situation, Kuipers proposed to simply cut the bunds of the ricefields whenever they remained uncultivated.

Discussion

In Indonesia, before World War II, vector breeding sites were identified by medical entomologists on the basis of larvae finds. A breeding place was considered dangerous when it contained sufficient quantities of the larvae of a malaria-transmitting mosquito.

With growing experience, entomologists learned more about the specific breeding habits of dangerous vectors. This, of course, facilitated their search for larvae, as they now knew more or less where to look. There are breeding sites, however, that are dangerous only during certain periods of the year, or—as we saw with the Brengkok epidemic—only under abnormal circumstances. So in such cases, an entomological approach based on larvae finds could easily fail to indicate dangerous breeding sites.

“Kuipers tried to combine the information on the specific breeding habits with meteorological and other readily available technical data so that he could predict not only where, but when, to expect dangerous breeding sites. Or, perhaps more correctly put, when and where to expect a combination of environmental factors that would make a particular area a suitable breeding site for a suspected vector.

Kuipers claimed that his method not only meant considerable savings in the amount of entomological field work required, but that by pinpointing the potential breeding sites he could also bring down the cost of the sanitation work.

An example of this can be found in Kuipers' thesis "Mathematical-statistical processing of data on *Anopheles* in the Netherlands and Java" (in Dutch), which he produced 4 yr after the publication on the Brengkok epidemic. He says, "Another application is the sanitation of Patjitan, a town of some 8,000 souls on Java's southern coast. In 1929, on the basis of larvae findings, the sanitation of this town was considered impossible due to excessive cost, which was estimated at 200-300 thousand guilders (25 guilders per inhabitant).

"With the deductive method, it appeared that the area that needed to be sanitized was much smaller than previously expected. On this basis, a sanitation project was implemented in 1934 on a budget of 4,000 guilders; this is only half a guilder per inhabitant."

In his thesis, Kuipers also discussed the application of multiple regression analysis to isolate the effects of interrelated environmental vectors on vector density. And he used regression analysis to explain the mystery of *A. subpictus,* which transmitted malaria in one location but not in another that was practically identical. From his calculations, he concluded that there were, in fact, two species that the entomologists were having difficulty in telling apart.

Experienced medical entomologists have now become an even rarer species than they were in Kuipers' day, while the gathering and processing of data have much improved. It is therefore a logical proposition to further explore the direction taken by Kuipers. The relevance of such an exploration, however, depends on the answers to the following questions:

- Has anyone outside Indonesia tried a similar approach?
- Are there any circumstances specific to Indonesia that would make the approach inapplicable elsewhere?
- Have any new scientific developments rendered the approach obsolete?

Reference cited

Kuipers J, Stoker W J (1934) A malaria epidemic caused by *Anopheles ludlowi* in East Java in 1933 [in Dutch]. Med. J. Dutch East Indies 74(2):74-90.

Notes

Author's address: W. B. Snellen. International Institute for Land Reclamation and Improvement. P.O. Box 45, 6700 AA Wageningen, Netherlands.

Citation information: International Rice Research Institute (1988) Vector-borne disease control in humans through rice agroecosystem management. P.O. Box 933, Manila, Philippines.

Proposed curriculum on disease vector management in water resources development projects for engineering courses

R. BAHAR

Planning, design, construction, and operation of water resource development projects usually cover only engineering, technical, and financial aspects. There is rarely a thorough understanding of their environmental and health implications. Most environmental management measures that can be incorporated into these projects to safeguard health are consistent with good engineering practices. Therefore there is a need to increase the awareness of engineers, in particular, concerning these implications, and train them to adequately deal with possible health risks. Courses at different technical levels are proposed, from the technician's level, with a focus on information transfer to farmers, to research-oriented postgraduate courses. The objectives and target groups for each level are discussed. Professional development courses for practicing engineers are also recommended. The scope, learning objectives, curriculum content, and evaluation of 4 courses ranging from 5 h to 6 wk duration are presented.

In water resources development projects (WRDPs), the design and management of a project affect not only productivity (income) but also the health, social, and economic relationships of the population and their potential for further development.

Yet planning, design, operation, and monitoring of WRDPs are generally undertaken by agencies and individuals with specialized expertise that focuses mainly on technical and financial aspects of projects. There is rarely any understanding of the health and environmental impact.

Most environmental management measures for reducing the health hazards of WRDPs are consistent with good engineering practices and are cost-effective. The development and application of environmental management measures, especially those of a more sophisticated nature, are most feasible in major WRDPs. Because of the importance of such projects to national economic development and the relative availability of qualified technical personnel and other resources, many types of environmental management can be planned and applied in these WRDPs and regularly evaluated and maintained.

Because of the interdisciplinary character of vector-borne disease management and control in WRDPs, there is a need for various science, engineering, and managerial skills. This does not imply, however, that extra manpower is required. Rather that the health hazards of WRDPs and their control, especially those that can be accomplished by environmental management, should be added to the curricula of professional training of all staff engaged in WRDPs. Alternatively, short in-service training courses can be organized for project staff so that skills can be transferred and staff reoriented to cope with project problems. The role of engineering colleges should be defined and their collaboration obtained to include health aspects of WRDPs in their curricula.

To provide guidelines for engineering colleges, the Water Management Department, Silsoe College, Silsoe, U.K., and the World Health Organization met, in September 1986, to develop a health hazards and control curriculum for engineering courses. The objectives of this meeting were to

- encourage the incorporation of procedures for preventing disease transmission from initial stages—surveys, planning, and design;
- call the attention of planners, designers, and engineers (civil, irrigation, hydraulic, and agricultural) to the health implications of their work;
- produce a curriculum on the health implications of WRDPs and the applicable environmental management measures for disease vector management;
- recommend a course syllabus for health implications of WRDPs; and
- list references and teaching aids for subjects recommended in the course syllabus.

By following the steps shown in Figure 1, a generalized curriculum covering the learning objectives and content of a course for engineers was developed. More detailed guidelines for syllabuses for courses of various durations were also drafted.

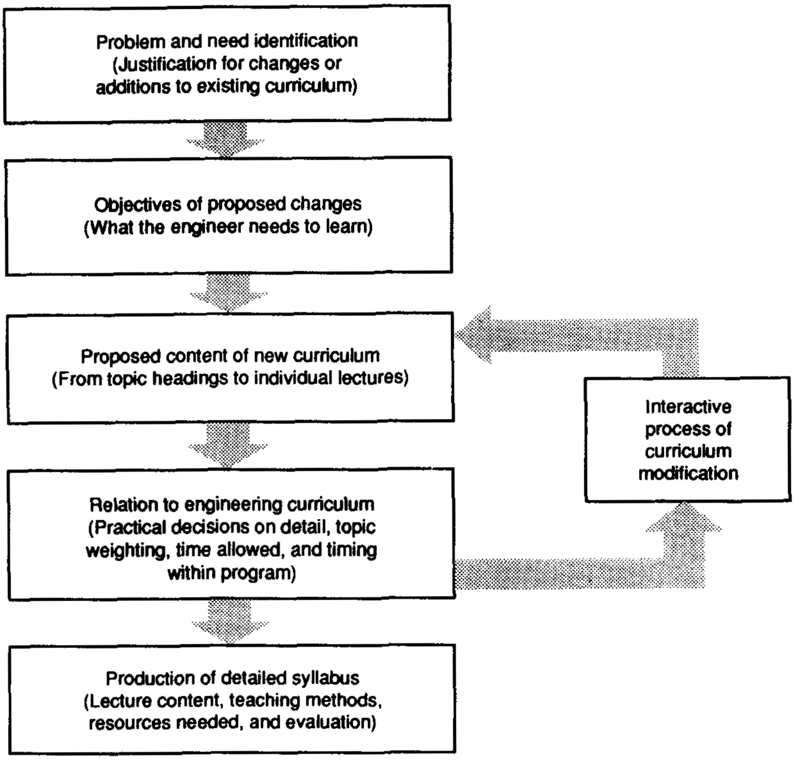
Types of courses proposed

Training institutions should offer courses for technicians, undergraduate engineers, and postgraduate students, and short, courses for professionals in environmental management.

Technician level

At the technician engineer, or subprofessional, level, it is important to instill some understanding of the reasons for environmental management. Usually in irrigation schemes, the technically qualified and the vocational staff are the most numerous and the ones in closest contact with farmers and their families. If environmental management measures, particularly those relating to the operation and maintenance phases of WDRPs, are practiced, it is usually the subprofessional staff who have to implement them and enforce them if necessary. It is far better to persuade and explain the reasons for environmental management to farmers than to enforce inexplicable rules in an authoritarian fashion.

The emphasis should be on the explanation, in simple visual terms, of the epidemiology and control of vector-borne disease. Ideally the education of technicians-engineers should include training in instructional techniques to enable them to fulfill an extension role more effectively.



1. Methodology of curriculum development.

Undergraduate level

At the undergraduate level we are dealing with civil, agricultural, public health, and water engineers, and, to a lesser extent, with students in planning and rural development who may take common service courses with engineers.

The primary aims of exposing undergraduates to environmental management approaches are to make them aware of the issues involved and to introduce them to the disciplines of vector biology, ecology, and disease epidemiology. Ideally this should be done in the context of a more general environmental impact assessment, and should be introduced early in undergraduate programs.

Later, the more detailed techniques of environmental management should be reviewed and related to the design and management of WRDPs. The objectives of undergraduate engineering studies should be to

- demonstrate the often adverse environmental effects of engineering projects in general, and WRDPs in particular;
- introduce students to environmental impact assessment methods;
- instruct students on the effects of WRDPs on public health;
- describe practical environmental management approaches that can be used by engineers;

- cast environmental management measures in the context of wider integrated control strategies; and
- familiarize students with the roles and approaches of vector and health specialists, and to encourage professional collaboration between disciplines.

Postgraduate level

At the postgraduate level, students take specialized courses (hydraulic engineering, irrigation engineering, and agricultural engineering) or work toward research degrees.

In postgraduate courses there should be more time available for environmental management courses than at the undergraduate level. Usually a wider variety of teaching techniques are used: case studies, seminars, visiting specialists, and individual and group project work. The objectives at the postgraduate level, however, are essentially the same as those for undergraduate courses.

Postgraduate training should concentrate on research and the development of techniques, models, and approaches to environmental management. It is essential that feedback gained through these activities ensures up-to-date and authoritative curricula.

Professional development

Short courses and workshops are generally brief (1-3 wk) intensive periods of group training. Professional development refers to individual study of longer duration (weeks or months) and may include secondment to research institutions or commercial firms.

Proposed curriculum

Scope

In-service training in environmental management for engineers can be accomplished through short courses, workshops, and professional development programs.

The curriculum for four modules is proposed. Learning objectives and curriculum content are applicable to a Course or module of any duration from 5 h to 6 wk. The guidelines (Table 1) consider 4 course durations: 5- and 10-h workshops, and full-time short courses of 35 h (1 wk) and 205 h (6 wk).

The curriculum focuses on the role of the engineer in disease vector management and is divided into five sections:
1) experience from WRDPs (case studies), 2) diseases, 3) vectors, 4) control methods, and 5) the role of the engineer.

In practice these sections would be taught in an integrated manner. It is convenient, however, to consider them separately from the development of the overall curriculum and the syllabi.

The curriculum focuses on malaria and schistosomiasis because they are very important. Other vector-borne diseases are mentioned, but they would not be taught in detail unless they were of local importance.

Table 1. Proposed weighting of curriculum units by hours and percentage of instructional time in 4 module or courses of 5, 10, 35, and 205 h duration.

Unit	Time (h) and percentage (%) of total for each unit)							
	5-hour module		10-hour module		35-hour course		205-hour course	
	h	%	h	%	h	%	h	%
Case studies	1	20	2	20	7	20	32	16
Diseases	1	20	2	20	5	14	20	10
Vectors	1	20	2	20	11	31	66	32
Control methods	1.5	30	3	30	10	29	80	39
Role of engineer	0.5	10	1	10	2	6	7	3

Learning objectives

Whether one is dealing with a self-contained short course or with a module within an engineering degree program, the learning objectives would be to give the student or practicing engineer

- an understanding of the impact of WRDPs on vector-borne, water-related diseases;
- knowledge of the life cycles, geographical distribution, present status, and clinical features of the major diseases of WRDPs;
- knowledge of the ecology of the major vectors (mosquitoes and snails) and impact of environmental changes on their preferred habitats in WRDPs;
- an understanding of the major disease-vector control methods, with special emphasis on environmental management; and
- an appreciation of the role of the engineers in relation to their own tasks, to professionals in other disciplines, and to personal protection of site staff.

In a 6-wk course for designers or participants in disease vector control programs, additional objectives would be for students to gain knowledge of

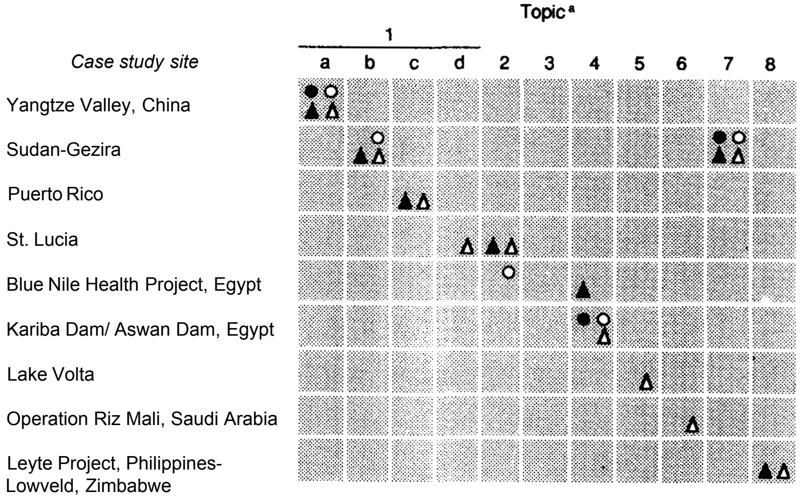
- disease vectors and vector survey techniques,
- principles of disease epidemiology and epidemiological survey techniques,
- major control methods and their problems, and
- control program management.

At the end of the training, the person would be competent to

- participate in planning and conducting field surveys to establish a disease vector control program,
- promote the incorporation of environmental management into the design and operation of WRDPs, and
- be a major participant in an integrated disease vector control program.

Curriculum content

A common curriculum is proposed for all four course lengths. The weighting of the five topics and the teaching methods vary for each course (Fig. 2, Tables 24). The



Case study site	Topic[a] 1 a	b	c	d	2	3	4	5	6	7	8
Yangtze Valley, China	● ○ ▲ △										
Sudan-Gezira		○ ▲ △								● ○ ▲ △	
Puerto Rico			▲ △								
St. Lucia				△	▲ △						
Blue Nile Health Project, Egypt					○		▲				
Kariba Dam/ Aswan Dam, Egypt							● ○ △				
Lake Volta								△			
Operation Riz Mali, Saudi Arabia									△		
Leyte Project, Philippines- Lowveld, Zimbabwe											▲ △

Key

Module-course	Time allotted (h)	Teaching Method				
		Slides	Anecdote	History	Visiting lecturers	Practicum
● 5-hour Module	1	✔	✔			
○ 10-hour Module	2	✔		✔		
▲ 35-hour Course	7	✔		✔	✔	
△ 205-hour Course	32	✔		✔	✔	✔

2. Topics by case-study site suggested for Case Study Unit in 4 modules or courses of 5, 10, 35, and 205 h duration.

resources required to implement the courses are 1) teaching staff, 2) publications and audiovisual aids, 3) demonstration materials and equipment, and 4) field sites.

Evaluation

The most effective method of evaluation is to involve students in problem solving exercises using real or hypothetical case studies. Individual or group projects should be done, especially during longer courses. Students would propose control strategies and identify the tasks of engineers and their roles in relation to other professionals. Ideally, the projects should be selected early in the course so that students could take advantage of class sessions to seek background information. Students' performance could be assessed based on oral or written reports submitted at the end of the course. Problem solving usually leads to research and development and results in innovative approaches to vector control management in WDRPs by engineers.

Table 2. Weighting of topics by hours (h) of total instruction time devoted to Diseases Unit in four modules or courses of 5, 10, 35, and 205 h duration.

Topic	Time (h) of total time devoted to each topic			
	5-hour[a] module	10-hour[a] module	%-hour[a] course	205-hour course
Life cycle causative agent	0.5	0.5		
Lecture			0.5	0.5
Demonstration				0.5
Clinical features and treatment				
Lecture			0.5	1
Epidemiology	0.5	1.5		
Lecture			2	6
Field work				3
Geographical distribution				
Lecture			1	2
Disease control, status, and perspective				
Lecture			1	2
Field work				5
Total	1.0	2.0	5	20

[a] All instruction by lecture.

Conclusion

By involving engineers with human health and disease vectors, the aim is not to turn them into entomologists or epidemiologists. Rather, it is to turn out better engineers—better because they are more fully aware of the impact of their activities, better because they can more effectively use their engineering for the good of mankind, and better because they will more willingly and comfortably cooperate with those of other professional disciplines.

Tabla 3. Weighting of topics by hours (h) of total instruction time devoted to Vectors Unit in four modules or courses of 5, 10, 35, and 205 h duration.

Topic	Time (h) of total time devoted to each topic			
	5-hour module	10-hour module	35-hour course	205-hour course
Medical importance of mosquitoes and snails				
Lecture			1	4
Mosquito biology and ecology				
Lecture		1	1	5
Laboratory			2	4
Mosquito behavior				
Lecture	1			4
Laboratory				4
Field work			2	24
Snail biology and ecology				
Lecture		1	1	7
Laboratory			1	4
How WRDPs create new vector habitats				
Lecture			1	2
Laboratory				4
Field work			2	4
Total	1	2	11	66

Table 4. Weighting of topics by hours (h) of total instruction time devoted to Control Methods Unit in four modules or courses of 5, 10, 35, and 205 h duration.

Topic [a]	Time (h) of total time devoted to each topic			
	5-hour module	10-hour module	35-hour course	205-hour course
Historical background	1.5	1.5	1	2
Chemical control			1	2
Biological control			1	2
Environmental control		1.5	3	11
Prevention and avoidance			1	2
Comprehensive vector control Integrated methods			1	4
Health education			1	2
Vector control methods Review-group discussion			1	3
Equipment and machinery demonstrations				16
Special problems Individual projects and class presentations				36
Total	1.5	3.0	10	80

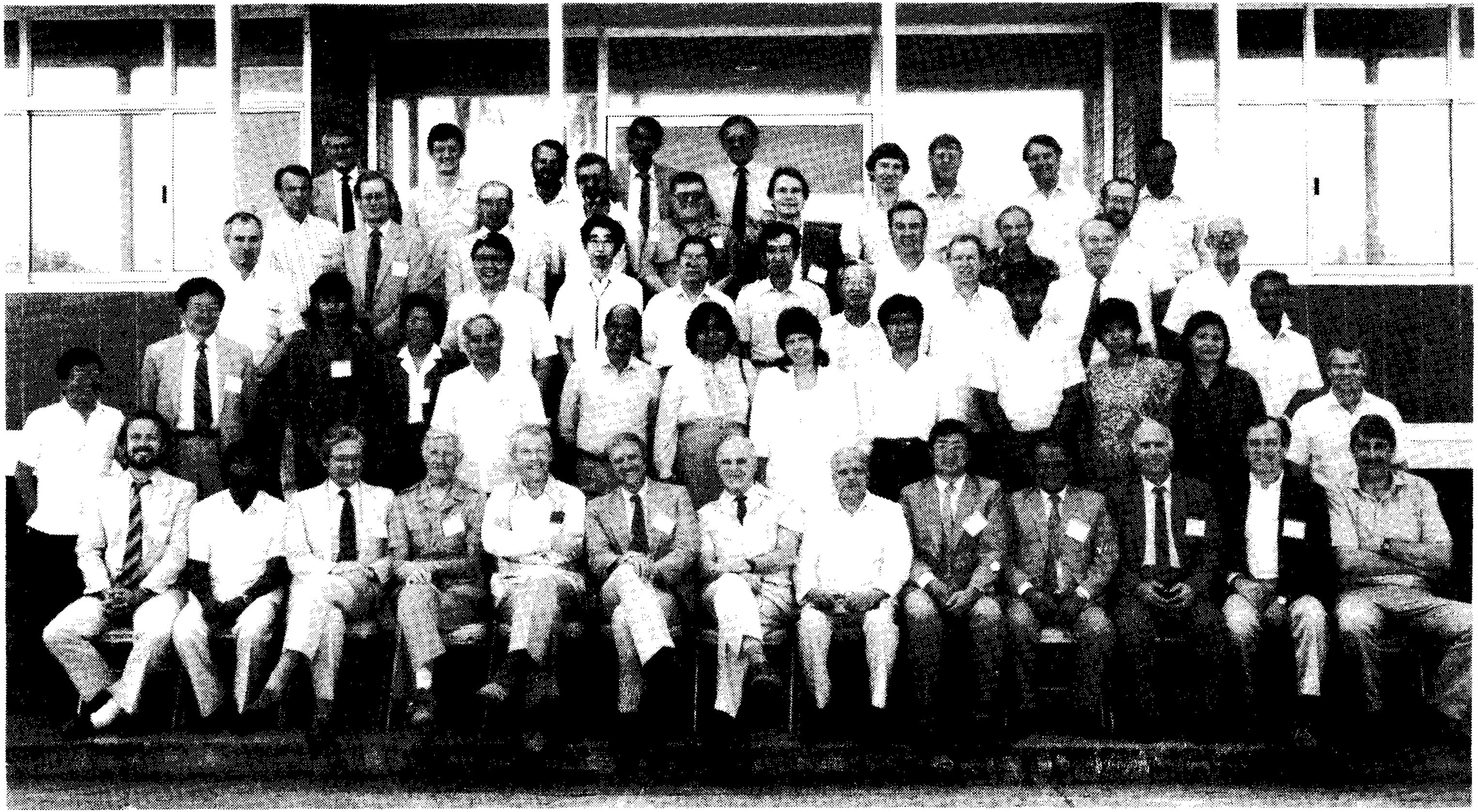
[a] All instruction by lecture.

Notes

Acknowledgment: This paper was adapted from Silsoe College, Water Management Department, and World Health Organization (1986). Information consultation meeting for development of curriculum and health management in water resources development projects for inclusion in engineering courses. Doc. VBC 87-1. Division of Vector Biology and Control, World Health Organization, 1211 Geneva 27, Switzerland.

Author's address: R. Bahar, Planning, Management and Operations Unit, Division of Vector Biology and Control. World Health Organization, Geneva, Switzerland. Current address: 9, Chemin des Colombettes, 1202 Geneve, Switzerland.

Citation information: International Rice Research Institute (1988) Vector-borne disease control in humans through rice agroecosystem managemen, P.O. Box 933, Manila, Philippines.



Workshop on Research and Training Needs in the Field of Integrated Vector - Borne Disease Control in Riceland Agroecosysterns of Developing Countries
IRRI, Los Banos, Philippines, March 9 - 14, 1987

Participants

F. P. Amerasinghe
Dept. of Zoology
University of Peradeniya
Peradeniya
Sri Lanka

A. Arata
Vector Biology and Control Project
1611 N. Kent, Suite 503
Arlington, VA22209
USA

A. Amentia
Project Development Dept.
National Irrigation Administration, EDSA
Quezon City,
Philippines

R. Bahar
Division of Vector Biology and Control
World Health Organization
1211 Geneva
Switzerland

Y. H. Bang
WHO Regional Office for Southeast Asia
World Health House
Indraprashta Estate
Mahatma Ghandi Road
New Delhi 110002
India

R. Bergquist
WHO/ World Bank/ UNDP Special Programme for Research and Training in Tropical Diseases
World Health Organization
1211 Geneva
Switzerland

S. I. Bhuiyan
IRRI, P.O. Box 933
Manila, Philippines

R. Bos
Division of Vector Biology and Control
World Health Organization
1211 Geneva
Switzerland

D. J. Bradley
Ross Institute for Tropical Hygiene
London School of Hygiene and Tropical Medicine
Keppel Street
London WCIE 7HT
United Kingdom

B. Cariaso
Dept. of Entomology
University of the Philippines at Los Baños
College, Laguna
Philippines

Gelia T. Castillo
Dept. of Agricultural Education
University of the Philippines at Los Baños
College, Laguna
Philippines

L. Cowper
Communicable Disease Division
Bureau of Science and Technology, USAID
Washington, DC 20053
USA

D. A. Dame
United States Department of Agriculture
Agricultural Research Service
P.O. Box 14565
Gainesville, FL 32064
USA

Cristina C. David
IRRI, P.O. Box 933
Manila, Philippines

S. K. De Datta
IRRI, P.O. Box 933
Manila, Philippines

E. S. Erce
Schistosomiasis Control and Research Service
Ministry of Health
San Lazaro Compound
Sta. Cruz, Manila
Philippines

J. C. Flinn
IRRI, P.O. Box 933
Manila, Philippines

M. S. Fritsch
Institute for Land Improvement and Water Management
Swiss Federal Institute of Technology
ETH-Hoenggerberg
CH-8093 Zurich
Switzerland

E. Garcia
Institute of Public Health
University of the Philippines
625 Pedro Gil
Ermita, Manila
Philippines

D. P. Garrity
IRRI, P.O. Box 933
Manila, Philippines

K. G. A. Goonasekere
Dept. of Agric. Engineering
University of Peradeniya
Peradeniya
Sri Lanka

N. G. Gratz
Chemin Pont-Ceard 42
1290 Versoix (GE)
Switzerland

Hu Ching-li
WHO Representative
Ministry of Health
San Lazaro Compound
Sta. Cruz, Manila
Philippines

T. Indiati
Communicable Disease Control and Environmental Health
Ministry of Health
Jakarta
Indonesia

A. Kandiah
Water Resources Development and Management Service
Land and Water Development Division
FAO of the United Nations
Via delle Terme di Caracalla
Rome
Italy

B. H. Kay
Vector Biology and Control Unit
Queensland Institute of Medical Research
Bramston Terrace
Herston, Brisbane
Australia

C. Leake
Dept. of Entomology
London School of Hygiene and Tropical Medicine
Keppel Street
London WC1E 7HT
United Kingdom

J. A. Litsinger
IRRI, P.O. Box 933
Manila, Philippines

Lilia de las Llagas
Institute of Public Health
625 Pedro Gil
Ermita, Manila
Philippines

Lu Baolin
Dept. of Vector Biology and Control
Institute of Microbiology and Epidemiology
P.O. Box 130
Beijing 100800
China

T. H. Mather
8 Woodstock Close
Off Woodstock Road
Oxford OX2 8D8
United Kingdom

Moa Bi-jun
Guangdong Academy of Agricultural Sciences
Rice Research Institute
Guangzhou, Guangdong
China

C. L. Meek
Dept. of Entomology
402 Life Sciences Building
Louisiana State University
Baton Rouge, LA 70803
USA

M. Mogi
Division of Parasitology
Dept. of Microbiology
Saga Medical School
Nabeshima, Saga 840-01
Japan

J. A. Najera
Malaria Action Programme
World Health Organization
1211 Geneva
Switzerland

J. Olivares
Agricultural and Rural Development
Department
The World Bank
Room 1133
1818 H Street, N.W.
Washington, DC 20433
USA

J. K. Olson
Dept. of Entomology
Texas A&M University
College Station, TX 77843
USA

L. Padua
Entomology Department
University of the Philippines at Los Baños
College, Laguna
Philippines

M. D. Pathak
IRRI, P.O. Box 933
Manila, Philippines

C. Rees
Irrigation and Rural Development Dept.
Asian Development Bank
P.O. Box 789, Manila
Philippines

S. Salandanan
System Management Dept.
National Irrigation Administration, EDSA
Quezon City
Philippines

Nelia Salazar
Research Institute for Tropical Medicine
Alabang, Metro Manila
Philippines

F. T. Sanchez
National Crop Protection Center
University of the Philippines at Los Baños
College, Laguna
Philippines

M. N. Santos
Malaria Eradication and Control Program
Ministry of Health
San Lazaro Compound
Sta. Cruz, Manila
Philippines

C. Schaefer
Mosquito Control Research Laboratory
University of California
Kearney Agriculture Center
9240 S. Riverbend Avenue
Parlier, CA 93648
USA

L.S. Self
World Health Organization
Regional Office for the Western Pacific
P.O. Box 2932, Manila
Philippines

V. P. Sharma
Malaria Research Center
22 Sham Nath Marg
Delhi 110054
India

B. M. Shepard
IRRI, P.O. Box 933
Manila, Philippines

R. Slooff
Division of Vector Biology and Control
World Health Organization
1211 Geneva
Switzerland

W. H. Smith
IRRI, P.O. Box 933
Manila, Philippines

W. B. Snellen
International Institute for Land Reclamation
and Improvement
P.O. Box 45
6700 AA Wageningen
The Netherlands

M. S. Swaminathan
IRRI, P.O. Box 933
Manila, Philippines

Y. Wada
Dept. of Medical Entomology
National Institute of Health
10-35, 2-Chome
Kamiosaki, Shinangawa-Ku, Tokyo
Japan