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THE POTENTIAL OF INTERMITTENT IRRIGATION FOR INCREASING RICE YIELDS, LOWERING WATER CONSUMPTION, REDUCING METHANE EMISSIONS, AND CONTROLLING MALARIA IN AFRICAN RICE FIELDS

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ABSTRACT. Rice production in sub-Saharan Africa has more than doubled in the last 3 decades and the potential to further develop rice-harvested areas is considerable. Several studies have demonstrated that the transformation of arable land into rice irrigation might create suitable habitats for large populations of disease vectors. Prominent among those are anopheline mosquitoes responsible for transmission of malaria. The method of irrigation on an intermittent basis during the rice-cropping calendar has gained renewed interest as a potentially effective malaria control strategy since the early 1980s. We review the experiences of the past 80 years with intermittent irrigation in the cultivation of rice. This method has been shown to reduce significantly the density of malaria vectors by curtailing their larval development. Furthermore, reduced methane emissions and water savings with at least equal yields were achieved in intermittently irrigated rice fields. We explore and discuss under what conditions intermittent irrigation might be beneficial in new rice-growing areas and identify steps that have to be taken to expand such programs in the future.

KEY WORDS Malaria, intermittent irrigation, rice fields, Africa, vector control, environmental management

INTRODUCTION

The world's population is projected to grow from the current 6 billion people to about 9.4 billion by 2050. The last 4 decades have seen unprecedented demographic events, as dramatic changes in fertility, mortality, and population growth rates occurred, with more people added to the world's population over the past 50 years than in the preceding million years (Raleigh 1999). Unfavorable climatic conditions and inappropriate systems for access and distribution of agricultural products contribute to serious threats of food security. By 2020, the global demand for maize, rice, and wheat is estimated to increase by approximately 40%. This translates to an average annual increase of about 1.3% (Mann 1999). At present, more than 800 million people, predominately women and young children, are chronically malnourished. A recent report published by the United Nations Food and Agriculture Organization (FAO 2001) emphasizes that 17 countries in sub-Saharan Africa currently are facing exceptional food emergencies as a result of persistently difficult weather conditions, and ongoing civil strife or war. Food imports and aid to Africa have risen to unprecedented levels in the past few years. Every year, African countries buy approximately 3 million tons of rice, but food aid does not offer a permanent solution.

Rice is the staple crop for about one half of the world's population (Fischer et al. 2000). Rice is by far the predominant crop on the Asian continent. The importance of rice to national food security is further increasing in Asia and elsewhere. In the 1950s and 1960s, the Green Revolution and its underlying technological advances led to major increases in grain production, mainly through the development of high-yield varieties. However, we are currently confronted with an evident decline in the rate of crop yields (Conway and Toenniessen 1999). An increase in the production of food in general, and rice in particular, is urgently required.

Irrigation has played an important role in increasing agricultural output since ancient times and will be a part of future strategies to enhance food production. At present, only 8.5% of Africa's agricultural production systems are under irrigation (FAO 1997), but recent trends have shown that irrigation increases by about 1% per annum, and considerable potential exists to develop rice-harvested areas further.

Concern is rising in public health circles that agricultural gains may be associated with substantial negative health consequences. A large body of literature documents increases in vectorborne diseases that are consequential to the introduction of new irrigation schemes. Currently, malaria accounts for 300–500 million clinical attacks and more than 1 million deaths every year, mainly of children under the age of 5 in sub-Saharan Africa (WHO 1998). Almost 90% of the global burden of malaria currently is concentrated in sub-Saharan Africa (WHO 1999). In addition, recognition is growing that the release of methane from stably flooded rice fields plays an important role in climate modification. Pressure to conserve freshwater also is rising dramatically on a worldwide scale.

The purpose of this paper is to review the literature on intermittent irrigation in rice field ecosystems as a potential strategy for reducing malaria vector densities, increasing rice yields, and lowering water consumption and methane emissions. We first introduce the main rice ecosystems in the world and place particular emphasis on rice agriculture in Africa. We then summarize the experiences made over the course of the past 80 years, since the 1st experimental trial with intermittent irrigation was carried out in a rice field in Bulgaria. We clarify the circumstances under which water conservation, increased rice production, and reduced methane emission might be simultaneously achievable. Finally, we identify concrete steps that can be taken to expand such programs in the future. Progress will depend on a subtle interplay between economic, political, and scientific issues.

RICE ECOSYSTEMS

Rice is 1 of the major food grains of the world. The development of high-yield rice varieties and, consequently, lower prices have enhanced the importance of this crop. In 1996, rice was the predominant crop for 2,890 million people in Asia, 40 million in Africa, and 1.3 million in the Americas (FAO 2000). Some 120,000 varieties of rice are estimated to exist worldwide and research is ongoing to develop and promote new rice varieties. Rice is the most common crop under irrigation, because water affects the physical character of the plant, as well as the nutrient and physicochemical characteristics of the soil (Self and de Datta 1988). Field duration is usually between 90 and 120 days, but new varieties often mature earlier.

The technological advance that led to great achievements in rice production over the past 40 years was the development of high-yield rice varieties. Especially in Asia, this resulted in an enormous increase in rice yields. Growth in grain harvests even exceeded population growth between 1960 and 1985, at least partially because of the Green Revolution. Technical approaches to increase the yield and yield stability included modification of plant types, with an increase in number of grains per panicle, rice hybrids, and the selection of desirable recombinants. Biotechnological approaches such as cloned novel genes currently are under investigation (Khush 2001). However, expansion of the Green Revolution has also incurred costs to the environment, as fertilizers and chemical pest and weed control have led to pollution of freshwater bodies and groundwater through leaching. In addition, from 1985 onward, the growth in grain harvest fell behind population growth because of a slower increase of irrigation and fertilizer use. Overall, the adaption of new technologies has been a necessary but not sufficient condition leading to an increase in rice yield.

Current terminology distinguishes among 5 rice ecosystems: upland, very deep-water, deep-water, rain-fed lowland, and irrigated systems. Elevation, rainfall pattern, flooding, and drainage are the characteristics used to define these ecosystems. Upland rice, grown without surface water, is seeded on slopes. Yields are usually low because of the lack of moisture. Deep-water rice and very deep-water rice ecosystems are common in Southeast Asia. Rice plants are transplanted or seeded in flooded fields, usually adjacent to rivers or oceans. Therefore, the flooding patterns depend on rainfall, river flow, floodplain geomorphology, or tidal fluctuations. Soils in these ecosystems often suffer from salinity or toxicity. Rain-fed lowland ecosystems are predominant in relatively densely populated, poor rural regions and are typically characterized by considerable variation in flooding and yields depending on the pattern and the total amount of rainfall. Rain-fed rice often is grown in areas that are difficult to irrigate. Irrigated rice ecosystems now represent 55% of the world's harvested rice area and they contribute to 75% of the world's rice production. These ecosystems are characterized by control of the water level and high yields (IRRI 2002).

RICE AGRICULTURE IN AFRICA

In 2000, the total rice-harvested area of Africa was 7.7 million ha, a 5% share of the world's total. Within 3 decades, a 94% increase occurred in the area used for rice production. The rice-growing area in West Africa expanded by 144%, whereas expansion was considerably lower in eastern and northern Africa, at 59 and 36%, respectively (Fig. 1a). Over the same period, the total rice production increased by 135%, with the most dramatic increase occurring in West Africa (247%), followed by North Africa (130%). A significantly lower and only moderate increase was attained in East Africa (39%; Fig. 1b). The increase in irrigated land over the last 30 years is depicted on Fig. 1c. The irrigated areas grew by 48%. However, at present, irrigated agriculture is not practiced widely in West and East Africa. Here, rice production systems are dominated by upland rice. In West Africa, rain-fed and irrigated ecosystems only account for 15 and 11%, respectively. On the other hand, upland rice is grown in 54% of the area (Garrity 1988). In stark contrast, in North Africa, rice is grown mainly under irrigation with 1 crop per year.

Overall, irrigated land in sub-Saharan Africa lags far behind the rest of the world with only 3.5% of the land currently irrigated (FAO 2002). Irrigated agriculture in Africa can never sufficiently enhance food production on its own to keep up with the rapid growth of population. However, irrigation must be part of a broader strategy. Since 1970, the population has more than doubled in Africa (Fig. 1d). According to recent estimates, rice agriculture worldwide is expected to expand by 70% over the next 25 years to support increases in food demand (Schimel 2000).

Irrigation provides an opportunity for agriculture in arid areas and can stabilize yields in regions with unpredictable rainfall (Imevbore 1987). Africa has been the focus of several studies carried out under the auspices of the FAO, which attempted to assess

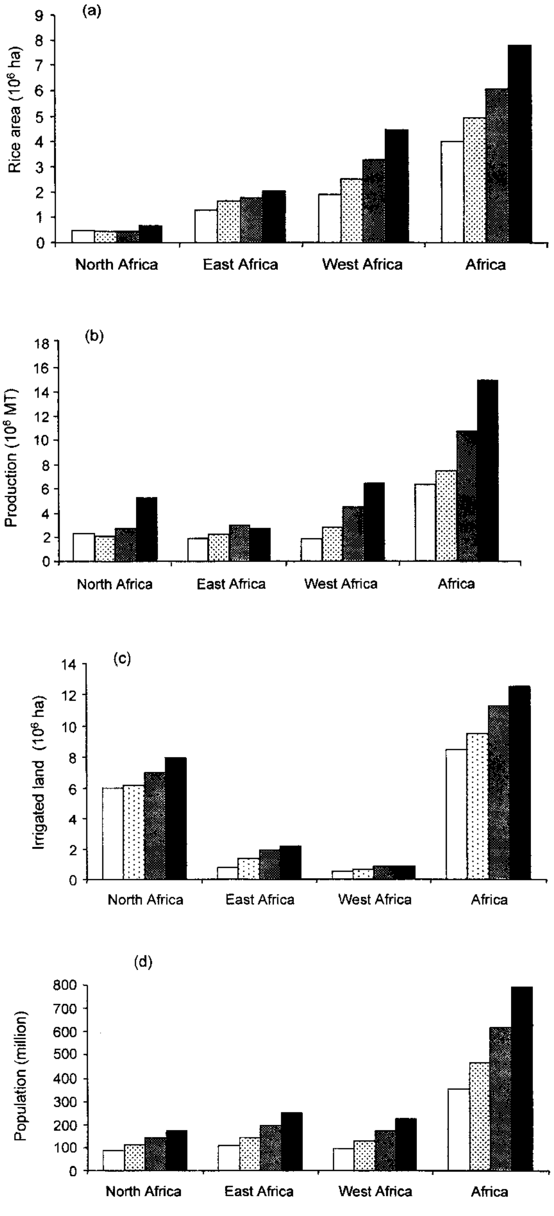

Fig. 1. Development of (a) rice-growing area, (b) rice production, (c) irrigation agriculture, and (d) total human population in Africa between 1970 and 2000 (open bars, 1970; light gray bars, 1980; dark gray bars, 1990; black bars, 2000).

areas suitable for agricultural production. The conclusion was made that Africa has an irrigation potential of 42.5 million ha. This is about 7% of the total area with soils and terrain potentially suitable for irrigation (600 million ha). At present, less than 30% of these 42.5 million ha are used for irrigation of any crops, and more than 50% of this area has been estimated to need rehabilitation before it could be utilized for irrigation. Country-specific information on soil conditions, water resources and potential for irrigation are displayed on several Web sites (FAO 2002). Four drawbacks must be kept in mind. First, 60% of the irrigation potential is located in humid regions, almost 25% in the Congo area alone. In these regions, rain-fed agriculture has traditionally dominated over irrigation (FAO 1997). Second, a considerable shortage exists of trained manpower for implementation, operation, and maintenance of irrigated systems. Third, fundamental aspects of existing land use patterns and human cultures and traditions must be considered before selecting a strategy for agricultural development. For example, substantial differences exist between East and West Africa (Ellis and Galvin 1994). Fourth, the introduction of large-scale rice irrigation projects might constrain biodiversity or change vector distributions. The possible ecological consequences must be carefully examined before implementation.

RICE PRODUCTION AND MALARIA VECTORS

With virtually no exception, the agricultural surveys to investigate the potential for irrigation in Africa do not consider that rice growing under irrigated water might create suitable habitats for malaria vectors. On the other hand, comparison between the maps of Africa's irrigation potential and malaria vector suitability areas (FAO 1997, MARA 2002) reveal almost identical distributions. Of the 5 rice ecosystems discussed above, upland rice, grown without water accumulation, is the only one not associated with malaria. However, the disease is linked to shallow and standing water bodies that often are created by traditional rice production. About one quarter of all *Anopheles* species that are known vectors of malaria are able to breed in rice fields (Carnevale and Robert 1987).

The introduction of irrigation with a network of canals and dams or the extension of wet periods for continuous rice cultivation establishes new aquatic environments (Bang 1988). Furthermore, the longevity of the mosquito is enhanced because of greater humidity during irrigation (Service 1989). In principle, rice fields may be habitable by different species of mosquito throughout all stages of plant growth (Lacey and Lacey 1990). Mosquito densities usually decrease as the plants develop, because mosquitoes have reduced access to the water for oviposition (Rafatjah 1988). In general, water depth, duration of flooding, temperature, crop growth rates, and the area of the rice field determine vector productivity (Bradley 1988). Furthermore, malaria transmission is greatly influenced by environmental and climatic factors, because vectorial capacity is strongly driven by humidity, rainfall, and temperature. Protective host genes, clinical immune responses, and parasite variation all contribute to malaria morbidity and mortality. Preproject data often are absent. Therefore, quantification of the relative contribution to overall malaria transmission of vectors breeding in rice field ecosystems is extremely difficult.

On the other hand, the association of rice production and incidence of malaria has been recognized for centuries. For example, this association resulted 1st in the regulation, and 2nd in the outlawing of rice cultivation, making rice growing a capital offense in Spain in 1489 (Lacey and Lacey 1990). Although the larger the production area of rice cultivation, the higher the expected density of anophelines, as demonstrated in China (Baolin 1988), this does not necessarily imply an increase of malaria incidence or an increased risk of exposure, as demonstrated in several African countries (for review, see Ijumba and Lindsay [2001]). Transmission intensities in communities living in close proximity to irrigation schemes can be higher, equal to, but also lower, when compared to villages outside rice irrigation systems (Ijumba and Lindsay 2001). The relationship between irrigated area under rice cultivation and the annual parasite incidence of malaria in India revealed a negative correlation in 23 states (Sharma et al. 1994). Rice cultivation in Burkina Faso even led to decreased malaria transmission, most likely because of the different vector status of *Anopheles gambiae* Giles in the rice-growing areas (Service 1989). In contrast, malaria epidemics were reported from various countries all over the world after rice transplantation (Surtees 1971). In Burundi, the vectorial capacity of *Anopheles arabiensis* Patton was shown to be 150 times higher in the rice field area compared to the cotton-growing area (Coosemans 1985). Consequently, it has been postulated that the impact of establishing new rice irrigation schemes on malaria might be less problematic in areas of high and stable malaria transmission. The social and economic development, often induced by increased rice production might be, at least partially, invested in antimalarial measures (e.g., purchase of insecticide-treated bed-nets), and hence contribute to a decline in malaria prevalence (Ijumba and Lindsay 2001). However, the creation of new rice fields in areas where malaria transmission is low may lead to epidemics and pose a great toll on primary health care systems (Najera 1988), as observed, for instance, in newly developed swamp rice areas in Sierra Leone (Gbakima 1994). In addition, agricultural development resulting in better socioeconomic conditions usually attracts labor from different regions, including workers from areas with low malaria transmission who are most vulnerable to malaria attacks.

The 2 most efficient malaria vectors in Africa, *An. gambiae* sensu stricto and *An. arabiensis,* have similar requirements for their larval habitats, but have distinct preferences for microhabitats. Importantly, the larvae of both species are found abundantly in man-made habitats and are able to readily adapt to anthropogenically induced environmental alterations or even to develop new behavior patterns (Collins and Besansky 1994). An important feature of *An. gambiae* is its preference for laying eggs in standing water near houses. With a flight range of about 1.5 km (Surtees 1971), indoor-resting densities of this mosquito are directly related to the distance of houses to rice fields. Climate suitability zones for *An. gambiae* show a large range, because these mosquitoes are found in areas with total annual precipitation of 330–3,224 mm. Distribution of *An. arabiensis* is restricted to areas with little variation in precipitation, ranging from 237 to 415 mm (Lindsay et al. 1998). Thus, *An. gambiae* predominates in saturated environments, with densities peaking during the rainy season, whereas *An. arabiensis* is more common in dry areas. Members of the *An. gambiae* complex breed in open pools, exposed to sunlight often in centers of rice fields. These mosquitoes tolerate high water temperatures, because sunlit pools often reach 40°C (Minakawa et al. 1999).

Anopheles nili Theobald and *An. moucheti* Evans are 2 malaria vectors of regional importance that breed at the edges of rivers and in the forest fringes, respectively (Fontenille and Lochouarn 1999). *Anopheles funestus* Giles is the main malaria vector in swampy habitats normally overgrown with vegetation and shaded breeding sites. Therefore, *An. funestus* might occur at high densities later in the growth period of rice.

EXPERIMENTAL TRIALS OF INTERMITTENT IRRIGATION FOR CONTROL OF MALARIA

Water regimens in controlled rice surface irrigation schemes can be categorized into 4 types: stable irrigation (constant water level with minimum supply to compensate for loss of water), renewal irrigation (constant water level with periodic renewal of water), fluctuating or flowing irrigation (constant water level with continuous irrigation and drainage), and intermittent irrigation (periodic irrigation and drainage) (Mogi 1988). Intermittent irrigation is the method of alternately irrigating and, passively or actively, drying the field for several days. The process starts about 2 wk after rice seedlings are transplanted and lasts for about 10–15 wk until the plants reach maturity. Intermittent irrigation is only feasible where climate conditions favor rapid drying. Draining rice fields during rainy seasons or in wetlands often is impossible.

It is important to note that intermittent irrigation was introduced in Asia about 300 years ago, primarily to obtain higher rice yields. The need for midseason drying to obtain higher yields also was recognized in Japan more than a century ago. Intermittent irrigation followed in the beginning of the 20th century. In 1955, a Japanese rice production contest was won by application of intermittent irrigation (Mogi 1988).

A series of experimental trials dating back to the 1920s has been carried out in different ecological and epidemiological settings to study the effects of intermittent irrigation as a potential tool for malaria control. The basic concept is to interrupt the reproductive cycle of the mosquito by withholding water on a periodic basis from the rice field. Because traditional rice fields are kept flooded for an entire cropping season, in certain areas even for 2 or 3 crops, multiple mosquito life cycles can be completed. In contrast, intermittent irrigation, curtails the development of the adult anopheline mosquitoes. Intermittent irrigation is particularly feasible in places where control of the water supply and drainage are possible. For best results, intermittent irrigation should be applied to all rice fields over large areas and during the entire cropping season. The method is less feasible in drought-prone areas, because water is too valuable to be drained. It is important to note that the rice field itself cannot be considered in isolation, and fallow fields, drainage ditches, or irrigation canals also must be monitored carefully because they provide optimal breeding places. For example, Knipe and Russel (1942) described in detail the filling of borrow pits and wells to eliminate vectors from channels and tanks.

The study designs and the outcomes of the trials of intermittent irrigation conducted in small experimental fields are summarized in Table 1. The first 3 studies (Konsuloff 1922, Ananyan 1930, Enikolopov 1931) were done in Bulgaria, Armenia, and Daghestan, respectively, 70–80 years ago. In the 2nd half of the 1930s, several experiments were conducted in Portugal (Hill and Cambournac 1941), Bali (Smalt 1937), and Indo-China (Antoine 1936). These countries were endemic for malaria at the time of trial implementations. In the early 1940s, experimental trials were extended to India (Knipe and Russell 1942, Russell and Knipe 1942) and Kenya (Grainger 1947). A paucity of further appraisal of intermittent irrigation existed for more than 3 decades, which can probably be explained by the advent and widespread application of indoor house spraying with DDT. Experiments with intermittent irrigation were continued from the mid-1970s onward in China (Luh 1984), India (Krishanasamy et al. 2000), Indonesia (Mather and That 1984), Japan (Mogi 1993), Kenya (Mutero et al. 2000), and Peru (Chang, personal communication). The method of intermittent irrigation is integrated into several current rice culture methods without special mention. For example, the World Health Organization reported intermittent irrigation to be successfully practiced in Korea (WHO 1983).

Although the trials were conducted in distinctively different ecosystems and the experimental designs varied from 1 site to another, 1 common feature occurred. Intermittent irrigation resulted in highly significant reductions in the density of larvae, pupae, and adult mosquitoes, reaching levels of up to 95%. It is now widely acknowledged that the wet period of the irrigation cycle must be controlled most carefully to reduce the density of malaria vectors. Konsuloff (1922) and Jettmar (1951) identified additional lethal effects such as sunlight, presence of fungi, or ants that feed on larvae in dried rice fields. The time required from egg deposition by *Anopheles* through larval development to the adult stage is approximately 18 days, depending on the species and its aquatic requirements (Hill and Cambournac 1941). Somewhat shorter cycles occur in the warmer tropics (Russell and Knipe 1942, Mather and That 1984). To prevent emergence of adult *Anopheles,* a marked moisture reduction of the soil is necessary. At present, little is known about the exact length of time that larvae and pupae can survive on dried soils. Some anecdotal evidence exists that soils with only 20% moisture are hostile environments and kill the majority of the larvae. Thus, larvae are unable to survive sufficiently long to complete the development cycle when the ground loses its surface water. However, several authors have described the longevity of eggs and larvae of *Anopheles* in dried soil (for review, see Jettmar [1951]). Annual rainfall patterns and complete soil drying must be considered. In 3 studies carried out in India, Kenya, and Tanzania, the soil did not dry completely and consequently, mosquito densities continued to be high (Grainger 1947, Krishanasamy et al. 2000, Van der Hoek et al. 2000). Because the physical characteristics of the soil influence the drying pattern, this must be kept in mind when designing the wet–dry cycles of intermittent irrigation. Reviewing the trials reveals that only scarce information is available about soil characteristics and water-holding capacities. Russell and Knipe (1942) designed a series of experiments with fixed wet periods of 5 days and dry periods varying between 1 and 5 days. Larval development was interrupted when the dry spells were 3 days or longer. Interestingly, a modified form of wet irrigation carried out in India, where the soil never completely dried out but instead left many pools of water, also showed a reduction in the density of mosquito larvae and pupae. Enhanced predation pressure in crowded puddles has been suggested as a possible reason (Rajendran et al. 1995). Information on the effects of malaria incidence and morbidity are missing in all but 1 of the studies. In the Senjayakollai area in India, Knipe and Russell (1942) observed a reduction of spleen rates in children from 48% to 4% and a reduction in parasite rates from 42% to 0% in the 1941 malaria season after introduction of intermittent irrigation. Future studies should monitor incidence rates and vector population densities to evaluate whether or not a causal link exists between intermittent irrigation and reduction of malaria morbidity. Rice yields and water-saving outcomes also should be quantified with great care, because these 2 outcomes are crit-

Table 1. Review of experimental trails that used intermittent irrigation in rice field ecosystems and appraisal of outcomes in terms of rice yield, malaria vector density, and clinical manifestations.

Trial setup					Trial outcomes		
Country, year (reference)	Area	Cycle	Rice variety	Malaria vector (*Anopheles*)	Rice yield	Vector density	Clinical manifestations
Bulgaria, 1920 (Konsuloff 1922)	Experimental plots	Several experiments, mainly 2 dry days	Not known	*An. maculipennis* (Meigen)	Not known	Not known	Not known
Armenia, 1928 (Ananyan 1930)	Experimental plots	Several experiments 3–6 days dry, 8–12 days watering	Not known	*An. maculipennis* *An. superpictus* (Grassi)	Yield of intermittent irrigation varied from −39% to +39% compared to continuous flooding	4–6 days drying resulted in complete interruption of larval development	Not known
Daghestan, 1930 (Enikolopov 1931)	Experimental plots	13 wet, 4 dry days	Not known	*An. maculipennis*	No harm to rice	Vector density reduced	Not known
Portugal, 1935–1939 (Hill and Cambournac 1941)	First experiment: 1.5 ha, half of the area irrigated intermittently	6 times: 10 wet days, 7 dry days (June–Sept.) use of active drainage	Chinez	*An. atroparvus* (Van Thiel)	Up to 35% higher yield in intermittent irrigated plots, 4 out of 15 intermittently irrigated plots resulted in lower yields, 2 of which had sandy soils;	80% reduction of large larvae in fields irrigated intermittently	Not known
	Subsequent experiments on other locations (different sizes and rice varieties)		Allorio, P6, Maratelli, Viallone (Italian fast-growing varieties)		10 out of 17 experiments with intermittent irrigation resulted in higher yields		
Indio China, 1936 (Antoine 1936)	Not known	3 wet, 3 dry days	Not known	Not known	Equal yield	100% reduction of larvae	Not known
Bali, 1937 (Smalt 1937)	15 ha	9 wet, 2 dry days	Not known	*An. aconitus* (Dönitz)	7.4% less yield with intermittent irrigation	75% reduction of larvae	Not known
India, 1940–1941 (Knipe and Russell 1942)	6 villages within 7 mi^2	4.5 days irrigation, 2.5 drying days (passive drying)	Not known	*An. culicifacies* (Gilles)	Not known	Breeding virtually stopped	Spleen rates in children reduced from 48 to 4%; parasite rates reduced from 42 to 0%
India 1938–1941 (Russell and Knipe 1942)	Experimental plots (2.5 acres)	5 wet, 1 dry days (active drainage) 5 wet, 2 dry days 5 wet, 3 dry days 5 wet, 4 dry days	Kattasalambalai	*An. culicifacies* (total of 10 *Anopheles* species	Higher yield in intermittently irrigated plots with no difference in nutritive value	No pupae found on wet days, but development into 4-stage larvae	Not known

Table 1. Continued.

	Trial setup				Trial outcomes		
Country, year (reference)	Area	Cycle	Rice variety	Malaria vector (*Anopheles*)	Rice yield	Vector density	Clinical manifestations
	Followed by village experiments	4.5 wet, 2.5 dry days				Shorter wet cycle proposed with 5 wet and 3 dry days reduced mosquito population	
Kenya, 1942 (Grainger 1947)	Experimental plots	Several schemes 3–5 wet, 4–7 dry days	Not known	*An. gambiae* *An. funestus* *An. pharoensis* (Theobald) *An. coustani* (Laveran)	Not known	Intermittent irrigation failed to control mosquito breeding because ground never dried completely	Not known
Taiwan, 1967 (Cates 1968)	10 field study sites	10 days flooding, then dried	Not known	*An. sinensis* (Wied.)	Not known	Intermittent irrigation controlled mosquito breeding	Not known
Japan, 1987 (Mogi 1988)	0.33 ha	5 wet days, temporary drying	Not known	*An. sinensis*	Not known	Drying reduced abundance of most mosquito species	Not known
China, 1978–1979 (Ge et al. 1981)	6,700 ha	2 wet, 5 dry days	Xindao 68-11	*An. sinensis*	7.6–11% higher yield	84–86% reduced larvae; 53–77% reduced adult densities	Not known
India, 1991 (Rajendran et al. 1995)	16.2-ha control block 22.3-ha intermittent irrigation blocks (soil type: clay)	Modified wet irrigation: reirrigation after most standing water had disappeared (but pools persisted) usually after 3–5 days	Short term rice varieties (J13, ADT 36, IR 36)	*An. subpictus* (Grassi)	4.5% higher yield in intermittently irrigated plot	57–88% reduction of pupae and larvae	Not known
Tanzania, 1995 (Van der Hoek et al. 2000)	Not known	4 wet, 3 dry days	Different varieties	*An. arabiensis*	8% less yield	No mosquito reduction	Not known
India, 1999–2000 (Krishanasamy et al. 2000)	Not known	3 water regimens: continuous irrigation, rotational water supply, intermittent irrigation	ASD 19	5 different *Anopheles* species	6–7% higher yield in intermittently irrigated plots	No mosquito control	Not known

Table 1. Continued.

	Trial setup				Trial outcomes		
Country, year (reference)	Area	Cycle	Rice variety	Malaria vector (*Anopheles*)	Rice yield	Vector density	Clinical manifestations
Kenya, 2000 (Mutero et al. 2000)	4 experimental plots of 0.4 ha	Control plots intermittent irrigation: 3 days flooded, 4 dry days (active drainage)	Basmati 217	*An. arabiensis*	No differences in yield between control and intermittently irrigated plots	Intermittently irrigated plots attractive environment for egg laying; however, low survival rates for larvae	Not known
Peru, 2001 (Chang, personal communication)	Control (permanent flooding) 304 and 238 m² 3-day dry period, 203 and 224 m² 6-day dry period, 148 and 160 m² 9-day dry period, 251 and 253 m²	4 water regimen: permanent flooding, 7 days flooding followed by 3, 6, or 9 dry days	Viflor	*An. albimanus* (Wied.), *An. pseudopunctipennis* (Theobald)	7 wet, 9 dry days increased rice yield by 22%	7 wet, 9 dry days reduced larvae production by 84%	Not known

ical to ensure farmer cooperation and ascertain their satisfaction.

A substantial literature exists that discusses the effects of drought stress during early rice development. Insufficient quantities of water during the earliest development stages can cause severe damage to the seedlings and, in turn, result in reduced yield. At this stage, the plant consumes a large amount of water, in opposition to the concept of intermittent irrigation. The results regarding the yield in the summarized studies are inconclusive. Higher, but also lower, yields were reported with intermittent irrigation and no association can be made between yield, water cycle, and rice variety. Previously, experiments carried out in various countries that were designed to establish the relationship between the quantity of water applied and rice yields also reported equal, higher, or lower rice yields. Several of these experiments are summarized by Van der Hoek et al. (2000). Use of rice strains that are tolerant of soil drought might be an advantage to simultaneously save water and obtain high yields.

INFLUENCE OF INTERMITTENT IRRIGATION ON SAVING WATER, REDUCING METHANE EMISSION, SOILS, AND WEEDS

Water currently is the most limiting resource for crop production and will be critical for the sustainability of rice production and the development of new irrigation schemes. In Asia, where water always has been regarded as an abundant resource, per capita availability declined by 40–60% between 1955 and 1990. Extrapolations indicate that most Asian countries will have severe water problems by the year 2025 (Riceweb 2002). Twice as much water is needed for rice growing as for the production of any other cereal. The traditional practice of continuous flooding of rice fields causes large water losses through deep percolation, especially if rice agriculture is further extended to permeable sandy soils (Sandhu et al. 1980). Therefore, future rice production will depend heavily on water-saving measures. Projects are underway to develop new rice varieties that mature earlier and are less water dependent. Other research focuses on the cultivation of wet-seeded rice. However, the overall trend is to conserve water in rice agriculture with well-adapted irrigation regimens.

High water-use efficiencies were obtained by intermittent irrigation as compared to continuous flooding in 2 studies in India (Jha and Chandra 1981, Pant et al. 1990). The soil characteristics were demonstrated to be of central importance. Sandy-type soils, with a low water-holding capacity, favor intermittent irrigation as a water-saving method. In contrast, prolonged drying of the rice fields, especially on clay soils, may result in cracking of the soil and hence increase the demand for water (Lu et al. 2000, Bouman and Tuong 2001).

Flooded rice fields are 1 of the major biogenic sources of atmospheric methane and therefore are important contributors to the greenhouse effect. The potential for methane release from rice fields has long been noted, but comprehensive measurements of methane fluxes in rice fields have been reported only since the early 1980s. Rice field methane is generated through microbial metabolic processes in the soil. These processes seem to be fuelled by root exudation and death, and methane is transported through the rice plant into the atmosphere (Redeker et al. 2000). Water regime, temperature, and soil properties, as well as rice variety, are the major factors determining the production and flux of methane in rice fields. Methane concentration has more than doubled during the last 200 years and a sustained increase is believed to contribute significantly to climatic changes. Thus, an intensification of rice agriculture is causing rising concern with regard to increased methane production. Water management was shown to have an enormous impact on methane emission rates: removing floodwater decreases methane emission, as a result of soil aeration. Several experiments conducted in different countries are summarized by Wassmann et al. (2001). Intermittent irrigation could be demonstrated to reduce methane emission by 15–88% (Sass et al. 1992, Wassmann et al. 2001).

Soil degradation caused by flooding has great effects on nutrition of higher plants. Products released by flooding are nitrogen gas, ferrous iron, sulfide sulfur, and organic acids, which alter the availability of soil nutrients (McKee and McKevlin 1993). Although continuous flooding has been reported to result in higher uptake of nutrients and thus a higher yield (Ogunremi et al. 1986), soils differ widely in their capacities to release nutrients. No general conclusion on the influence of the water regimen on nutrient uptake can be drawn. Indeed in some instances, drainage might be helpful for improving soil quality. Drainage results in control of salinity or acidity in problematic soils (Mathew et al. 2001), or the leaching of organic and inorganic toxins, which might accumulate in the soil because of low soil temperature (Neue and Bloom 1989).

Weeds are universal companions of rice fields, with yield losses reaching very high levels if the weeds are not controlled. The primary factors that encourage weed communities within rice field habitats are the water status of the field and the crop planting method. Maintaining standing water is believed to be an effective weed control practice because aerobic weed populations decrease with an increased water depth (de Datta and Baltazar 1996). This strategy is in direct opposition to intermittent irrigation. However, interactions among water and weed management practices are complex, and are further complicated by soil and climatic variability and heterogeneity. Furthermore, draining will expose aquatic weeds to dry conditions. Studies from the humid tropics on possible effects of tillage and water control on weed emergence and growth in the presence and absence of herbicides have yielded conflicting results, mainly because of site specificities (Bhagat et al. 1996). In addition, research on integrated weed management is ongoing, as scientists are developing environmentally sound weed management systems (Riceweb 2002).

CONCLUDING REMARKS AND PERSPECTIVES

Over the last 3 decades, rice production on the African continent has expanded enormously, and this growth most likely will continue in the near future. The development of high-yield rice varieties will further increase the significance of rice agriculture to secure global food production needs. The impacts of land and water development are diverse, and often are difficult to predict or are scarcely visible in the planning stage. Negative outcomes comprise the spread of malaria and other parasitic diseases (e.g., schistosomiasis) or further environmental pollution or water exploitation. Therefore, deliberate measures on environmental management must be taken to implement irrigation schemes in a way such that adverse health effects to rice growers and residents of the area are minimized and social and economic improvement prevails. We evaluated and found intermittent irrigation to be a potentially suitable strategy. Intermittent irrigation showed marked reductions in the young developmental stages of the malaria vectors. However, fields must be drained of all surface water to hold back mosquito breeding in small temporary puddles. This is not only important to reduce the density of anopheline mosquitoes, but also breeding of *Aedes* or *Culex* species, which are known to transmit other human disease pathogens, including filarial worms and arboviruses.

When integrated in a malaria control program consisting of a combination of measures, intermittent irrigation might also contribute to saving water and reducing methane emission with at least equal rice yields. Feasibility studies must be carried out to scrutinize the method under local conditions, because each setting has its own characteristics, which largely are driven by soil type, climate, and rice ecosystem. Intermittent irrigation requires sufficient flexibility to sequentially modify the intervention to obtain a high level of performance. Entirely missing, especially in those trials that failed to control mosquito breeding and displayed low yields, is an appraisal of how to adapt over time the wet–dry cycle to display the desired outcome. Adaptive tuning of this strategy to the local ecological settings might take several years until intermittent irrigation exhibits a high level of performance, as shown with other environmental management interventions for successful malaria control (Utzinger et al. 2001). Ongoing surveillance during pilot testing will help to determine new parameters for the protocol. Such a strategy is currently under way in Peru (Chang, personal communication). The characteristics of the soil are of central importance for sufficient drying without cracking, to save water and to curtail the development of adult mosquitoes. A rather high permeability and low water storage capacity is mandatory. Sandy soils, which display these characteristics, are common over large parts of Africa. Because rice agriculture has been extended to these soil types, intermittent irrigation could contribute to an enormous saving of water. Water drainage cannot be recommended on less permeable soils, and in regions where water is scarce. It has to be kept in mind that at present, rice in Africa is mainly grown under rain-fed conditions or as upland rice. These ecosystems are less suitable for intermittent irrigation. However, the area of irrigated rice agriculture is constantly growing in Africa. Nigeria and Sudan are 2 examples in which intermittent irrigation could be introduced on a large scale after careful evaluation. At present, Nigeria is the largest rice producer in Africa, with 16% of the rice agriculture currently being irrigated. Here, rice production has grown at an average of 14% per annum over the past 2 decades, which has resulted in an enormous expansion of the rice-growing area. The current rice-growing area in Sudan is relatively small but rapidly increasing. In 1997, total area was 2,940 ha, which has almost doubled over the last 3 years to reach a total area of 5,460 ha. In the same period, rice production was amplified by a factor of 4. Proposals to expand existing irrigation projects are underway and the construction of new hydraulic structures for new schemes has been launched. The potential risks of increased malaria incidence rates both in Sudan and Nigeria are high. Periodic malaria epidemics are reported each year, and these negatively influence social and economic development. Although the focus of the present paper was mainly on Africa, huge areas of irrigated rice fields in Asia provide appropriate conditions for the application of intermittent irrigation.

The recently launched Systemwide Initiative on Malaria and Agriculture (SIMA), with 120 field sites in Africa and Asia, might provide a suitable framework for pilot trials. One of the main objectives of SIMA is to bring together malaria and agricultural research. Interventions that have been proposed include water management practices to reduce mosquito breeding. In addition, the International Water Management Institute currently is implementing studies on intermittent irrigation in China and India. The Environmental Health Project in Madagascar currently is planning a 4-year program that will link and integrate activities in public health, population, and environment, including intermittent irrigation. Within these pilot trials, emphasis also must be given to education and training to assure proper operation and maintenance. Currently, the acceptance of farmers toward intermittent irrigation often is lacking, because the appreciation that intermittent irrigation not only reduces the risk of malaria but also might increase rice yield and save water is missing. Thus, effective information, education, and communication strategies are needed to accompany the promotion and implementation of intermittent irrigation. Intermittent irrigation might become more attractive for farmers as a water-saving method with at least equal rice yields, especially if water becomes more costly.

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