Malaria No More Japan
2022 report

Food Security and Human Health:

the Link Between Rice and Malaria in Sub-Saharan Africa

Forward

We are pleased to bring you this report on the link between rice cultivation and malaria risk in sub-Saharan Africa and the relation between food security and risks of infectious diseases.This publication was written at the request of The RBM (Roll Back Malaria) Partnership to End Malaria, a global platform of more than 500 partners, including private sector, NGOs, community organizations, foundations, research and academic institutions, to coordinate zero malaria activities, and with funding from the United Nations Foundation.Climate change and increasing economic activities with a growing population are causing ecological changes that are affecting our life and social infrastructure. In particular, it has long been pointed out that environmental changes can affect ecosystems and increase infectious disease risks. This report focuses on a literature review of the relation between ecosystem changes associated with the development of paddy rice cultivation in sub-Saharan Africa and the potential for increased infectious disease risks it poses.

Seven years after the United Nations General Assembly unanimously adopted "Transforming Our World: The 2030 Agenda for Sustainable Development" in 2015, we are witnessing a growing awareness of the Sustainable Development Goals (SDGs), as well as the importance of solving problems from a multidimensional perspective, in which the environment, economy, and society are inseparable parts of one another. The SDGs are also being recognized as an integral part of the environment, economy, and society. This report discusses the expansion of malaria risk from the perspective of both agriculture and infectious disease research. However, further detailed surveys, including field surveys, will be necessary in the future. As a preliminary study, this report suggests the importance of considering the risk of infectious diseases in agricultural and rural development projects and calls for further studies in the future. We hope you will read it.

Last but not least, the report was written in cooperation with many people, including Dr. Jo Lines, Professor of Vector Biology and Malaria Control of the London School of Hygiene & Tropical Medicine (LSHTM). We would like to express our sincere appreciation to Dr. Jo Lines, Ms. Kallista Chan, Research Uptake Manager, RAFT Consortium, LSHTM, Dr.Ali Ibrahim, Systems Agronomist at Africa Rice Center, and Dr. Kazuki Saito, Principal Scientist at Africa Rice Center.

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What is Malaria?

Mosquitoes kill more people than any other animal.
An African child dies of malaria every minute.

Malaria is the most serious mosquito-borne disease. Malaria is one of the three major infectious diseases, along with HIV/AIDS and tuberculosis.

It is caused by a parasite called *Plasmodium falciparum*, and is transmitted by the bite of a mosquito infected with the malaria parasite. The disease is transmitted when the *Plasmodium falciparum* enters the human bloodstream through the mosquito's salivary glands during the blood-sucking process necessary for the female anopheline mosquito to raise its eggs. The four endemic protozoa that cause malaria in humans are Tropical malaria (*Plasmodium falciparum* malaria), Tertian malaria (*P. vivax* malaria), Quartan malaria (*P. malariae* malaria) and Ovale malaria (*P. ovale* malaria), although several other types of *Plasmodium falciparum* such as Simian malaria (*P. knowlesi* malaria) have been reported to infect humans.

According to the World Malaria Report 2021 published by the World Health Organization (WHO) in December 2021, there were an estimated 241 million malaria cases and 627,000 malaria deaths worldwide in 2020. About 95% of malaria cases and 96% of deaths were concentrated in sub-Saharan African countries, and about 80% of deaths were children under 5 years old. This means that approximately one child dies from malaria every minute somewhere in the world.

Japan's Contribution to Zero Malaria

It was at the G8 Kyushu-Okinawa Summit held by Japan in 2000 that infectious disease control came to the fore as a diplomatic issue. At Japan's initiative, the "Okinawa Infectious Disease Initiative" was compiled and led to the establishment of the Global Fund (The Global Fund to Fight AIDS, Tuberculosis and Malaria) in 2002, to which major countries and others contributed funds. To achieve zero malaria, policies must be in place to ensure that all people have access to quality health services, including malaria prevention, diagnosis, and treatment. Immediate access to malaria diagnosis when there is a fever can be a matter of life and death. This calls for malaria control measures that ensure that no one is left behind, along with the strengthening of health systems. At the same time, it is important to apply the lessons learned from malaria control to date, such as prevention, multi-sectoral approaches, and new innovations, to achieving Universal Health Coverage (UHC).

Over the last 20 years, the burden of malaria in Africa has been greatly reduced by modern malaria interventions. Most of this reduction is attributable to the technology of long-lasting insecticidal nets (LLINs), which was first developed in Japan. Sumitomo Chemical's Olyset® net was the first LLIN to be developed and one of the first to be recommended by WHO. Since then, hundreds of millions of Olyset nets have distributed and used in endemic areas around the world. Later Sumitomo introduced the Olyset®Plus, a second generation mosquito net for resistance control, which was recommended by WHO's prequalification (PQ) scheme in 2018. The company's indoor residual spray, SUMISHIELDTM 50WG, which was launched under WHO PQ in 2017, is a residual-spray insecticide that is highly effective against mosquito populations that have evolved resistance to existing insecticides.

Meanwhile, as part of Japan's efforts to promote R&D for infectious diseases including malaria, the Global Health Innovative Technology Fund (GHIT Fund), Japan's first international public-private partnership, has invested approximately 12.3 billion yen, or about 44% of the cumulative total of 27.6 billion yen invested since 2013 (as of March 31, 2022), in the joint participation of domestic and foreign companies and research institutions in the development of malaria medicines and vaccines, etc. With the support of the GHIT Fund, exploratory research and pre-clinical trials of candidate anti-malarial drugs and vaccines are underway by research institutions and private companies, and the movement toward malaria-related R&D is expanding.

Food Security and Human Health: the Link Between Rice and Malaria in Sub-Saharan Africa

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Contents

Abstract

Demand for rice is growing rapidly in sub-Saharan Africa (SSA), and ministries of agriculture and international donor communities are promoting the expansion and intensification of rice cultivation for achieving self-sufficiency for rice in this region. Meanwhile, ministries of health are planning for the elimination of malaria. Both are desirable in Sustainable Development Goals (SDGs), but there is a serious concern about trade-off, because in SSA, rice fields in wetlands are a major breeding ground for the mosquitoes that transmit malaria. Our report shows that (i) the area under rice cultivation has been increasing and is expected to increase in SSA, (ii) a wide range of development programs have been supporting rice sector development without any concern about potential risk for increasing malaria infection, (iii) communities growing rice in SSA are exposed to greater malaria risk, and (iv) potential interventions exist for growing more rice with fewer mosquitoes. Based on these observations, the report suggests some future actions for both agriculture and health sectors.

1 History and progress in rice production in sub-Saharan Africa

a) Current and future trend in demand for rice in sub-Saharan Africa

Rice (*Oryza* spp.) is an important staple food crop and strategic commodity for food security and social stability in large parts of sub-Saharan Africa (SSA)[1]. Rice consumption has been increasing more rapidly than any other commodity and is driven by high population growth, urbanization and changing of consumer behaviour in the region (Figures 1, 2). Recently reaching a billion inhabitants, SSA has had the highest population growth rates in the world, where an average increase of 2.5% per annum was estimated between 2007 and 2016[2], During the same period, demand for rice across SSA has also increased, at a rate of 6% per annum. This demand is driven by urbanisation and a rising middle class with growing income, which have resulted in changes in consumption patterns and preferences away from traditional staple foods (such as millet and sorghum) and toward rice and other commodities[2] (Figure 2). Rice consumption in SSA is expected to continue growing in the foreseeable future because of the continent's high population growth rate and rapid urbanization[3].

Since the 1960s, rice consumption in SSA has exceeded its production (Figure 1). This gap between demand and local supply has gradually increased over the past 7 decades. In 2020, rice consumption was estimated to be approximately 32.2 million tons (MT) of milled rice, which was partially fulfilled by the importation of approximately 15.6 MT, an amount equivalent to 33% of that traded in the world market[4]. This indicates that in 2020, SSA had a self-sufficiency rate of only 48%.

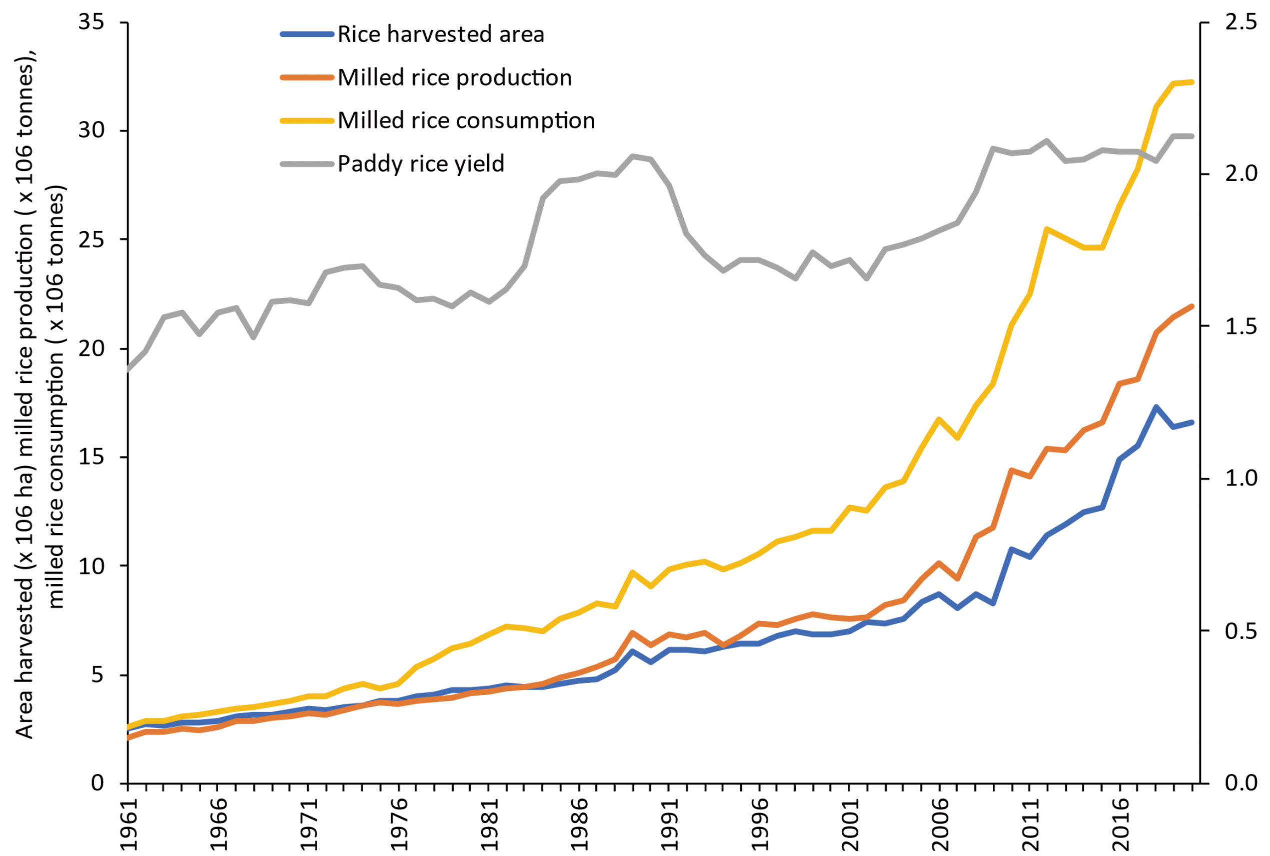

Figure 1. Trends in rice harvested area, milled rice production, consumption, and paddy rice yield in sub-Saharan Africa4.

In SSA, rice consumption per capita is around 30 kg/person/year, which is much lower than that of Asia (100 kg/person/year)[5]. However, there is large variation across countries. 11 SSA countries including Guinea, Madagascar, Mali, Côte d'Ivoire, Liberia, Sierra Leone, Benin, Guinea-Bissau, Comoros, Senegal, and Mauritania each consume more than 50 kg/person/year [4].

b) Trends in rice production: area expansion and yield increase

In response to its growing demand in SSA, rice production has progressively increased (Figure 1). This intensification was through enhancing rice yield per unit of land and the expansion of rice harvested area. Between 2000 and 2020, area harvested had increased from 6.9 million ha to 16.6 million ha (Figure 1), whereas rice yield increased from 1.7 tons per ha (t/ha) to 2.1 t/ha. Although rice yield in SSA has gradually improved over the years, recent yield levels are still much lower than the global average which is around 4.4 t/ha[3].

Despite recent increases in rice production, rice production has yet to catch up with consumer demand in SSA (Figure 1). Nevertheless, it is possible to close the gap between demand and supply in the region because of (a) the high intrinsic potential for the expansion of rice-growing areas and (b) the large differences between potential yield and actual yields obtained by farmers[6,7]. In terms of potential to expand rice cultivated areas, wetlands show great promise with an estimated total area of 239 million ha in SSA[6]. Here, wetlands are defined as areas where soil is saturated with water either permanently or seasonally. Furthermore, there is a large untapped potential for irrigation in Africa, extending to about 24 million ha or 1.8 times greater than the existing irrigation area[8]. On average in selected SSA countries, actual yields are only 38% of their potential[9].

This large gap between demand and supply for rice and substantial potential for rice increase in SSA as well as fears about global food security, which led to a spike in food prices in 2007–2008 gave African governments and the international donors' attention into efforts to strengthen the rice sector to achieve self-sufficiency in SSA[1,10]. For example, a policy framework known as the "Coalition for African Rice Development (CARD)" was launched in 2008, and in its second phase, the CARD aims to double rice production in SSA countries between 2018 and 2030[1].

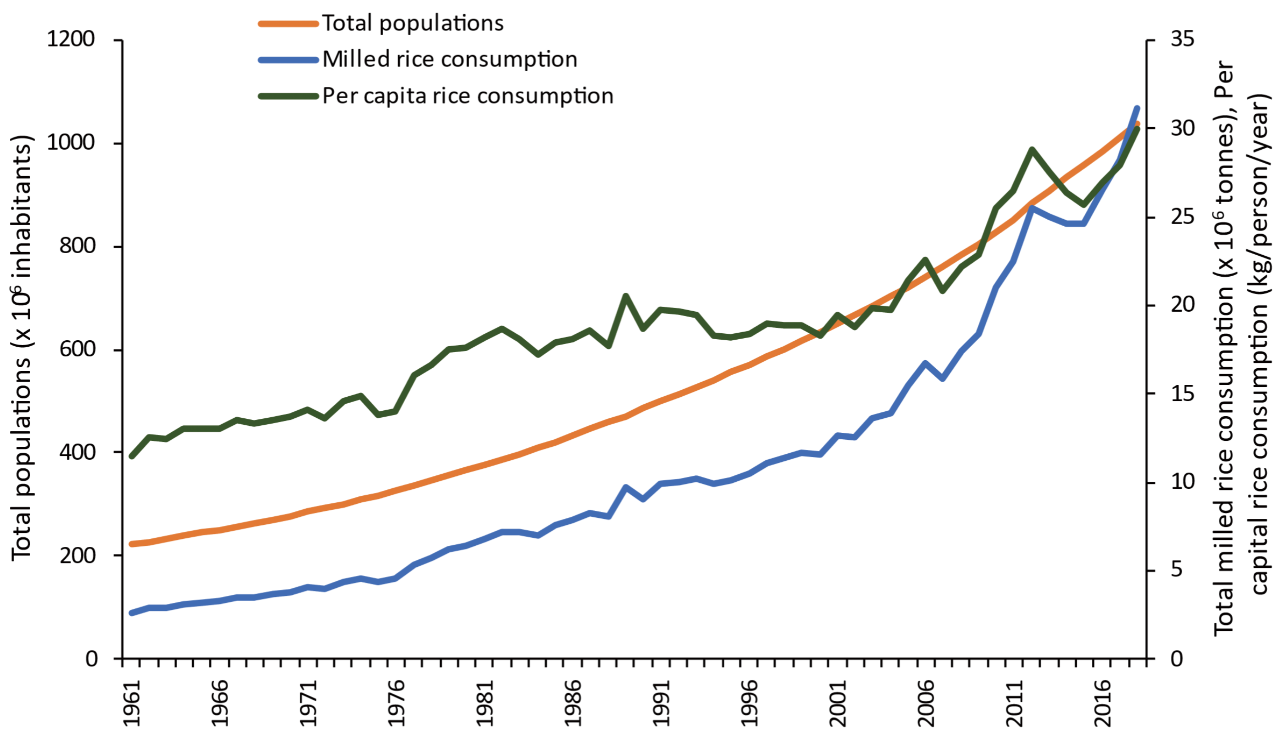

Figure 2. Trends in population growth, milled rice consumption, and per capita rice consumption (FAO, 2021)

c) Characteristics of rice cultivation in SSA and constraints to rice production

In SSA, rice production systems comprise irrigated lowland, rainfed lowland, and rainfed upland, with deepwater and mangrove rice being of minor overall importance. Irrigated lowland, rainfed lowland, rainfed upland, and others account for 22%, 40%, 35%, and 4%, respectively, of the total rice area in SSA[11]. Surface-water regimes and water sources (e.g., irrigation, rainfall, water table) distinguish the rice-growing environments. Irrigated lowland rice is grown in bunded fields with assured irrigation for one or more crops per year. Rainfed lowland rice is grown on level to slightly sloping, unbunded or bunded fields in lower parts of the toposequence and in inland valleys. Rainfed upland rice is generally grown on level or sloping, unbunded fields. Generally, irrigated lowland rice systems have higher yields than the other environments[9,12]. For example, on-farm surveys in 19 SSA countries showed that mean rice yields were 4.0, 2.6, and 1.6 t/ha in irrigated lowland, rainfed lowland, and rainfed upland, respectively. The yield obtained in irrigated lowland rice is close to the global average which is around 4.4 t/ha. This is against general perceptions of low rice yield in SSA, which have mainly arisen based on national-level statistics which do not differentiate production systems and their share of harvested areas. Low national yield level in SSA is attributed to larger area share of rainfed lowland and upland rice that give lower yields.

Low on-farm yields are caused by a range of biophysical and socioeconomic constraints that impose abiotic and biotic stress on the rice crop during its growth cycle[13]. Although the constraints are site- and production system-specific, soil-related constraints including iron toxicity and salinity, extreme temperature, drought (poor water management for irrigated lowlands), flooding, weeds, diseases, and suboptimal land and crop management interventions are the factors causing low yields[13–19]. For alleviating those constraints and enhancing rice yield in SSA, a wide range of technologies including new rice varieties and agronomic practices have been developed over 50 years[15,20–23].

d) Current focus in rice sector development in sub-Saharan Africa

As mentioned above, African governments and the international donor community have embarked on ambitious rice-development programs for rice sector development for achieving self-sufficiency for rice in SSA especially since 2008, when the 2007–2008 food crisis occurred. Many programs have focus on increased rice production and farmers' income from rice production, and enhancing competitiveness of locally produced rice (e.g. Coalition for African Rice Development (CARD[24]), Competitive African Rice Initiative (CARI[25]), RIKOLTO[26], National Rice Development Strategies (NRDS[27]). In addition to these, a few programs (CARI, RIKOLTO) recently initiated promotion of sustainable rice production, aligning with Sustainable Rice Platform (SRP). The SRP is a multi-stakeholder alliance with over 100 institutional members from public, private, research, civil society, and the financial sector, and promotes resource-efficient and sustainable production of rice, at farm to landscape levels. SRP aims to harness innovation to encourage farmers to adopt climate-smart, sustainable best practices, while enhancing smallholder livelihoods and protecting the environment. The SRP developed "SRP Performance Indicators" for environmental, economic, and social sustainability[28]. The indicators include profitability, labour productivity, yield, water productivity & quality, N-use efficiency, P-use efficiency, biodiversity, greenhouse gas emissions, food safety, worker health & safety, child labour & youth engagement, and women's empowerment. Such indicators help rapid, efficient, and robust monitoring of both development of agronomic practices and their scaling in agricultural research-for-development programs. However, it is noted that a wide range of agricultural development programs have supported rice sector development without any concern about potential risk for increasing malaria infection.

2 Trends in malaria infection and its control in sub-Saharan Africa

a) Malaria in sub-Saharan Africa

Malaria, a life-threatening disease caused by *Plasmodium* parasites, is a major public health problem. In 2020, there were an estimated 241 million malaria cases and 627,000 deaths worldwide. Thirty-two countries in sub-Saharan Africa (SSA) carry a disproportionately high share of these cases, and harbour 93% of all malaria deaths globally[29]. In areas of high transmission, the most vulnerable populations are young children, specifically those under 5 years of age, and pregnant women. The costs of malaria, from individual to national level, are enormous; it is estimated that the disease costs Africa US$12 billion per year.

SSA suffers more malaria than other regions because: (1) the predominant parasite species, *Plasmodium falciparum* is the deadliest of the human malaria parasites, (2) health systems are relatively weak compared to other regions, and most importantly, (3) the African malaria vector, *Anopheles gambiae* s.l., is the most efficient vector species in the world. It is efficient partly because it is very anthropophilic (i.e. high preference for feeding on humans for blood as opposed to other animals), but mainly because it has a long average lifespan. This allows the parasite to develop within the mosquito and be transmitted to humans. *Anopheles gambiae* can make use of a diverse range of breeding sites, including muddy footprints on a roadside, and it is especially well-adapted to ricefield conditions.

b) Trends in malaria infection in sub-Saharan Africa

There has been a general global decline in malaria transmission since the 1950s due to various efforts such as the Global Malaria Eradication programme (GMEP) in the 1960s. However, the big house-spraying campaigns of the GMEP were delivered mainly in Asia and Latin America. In most SSA countries, it was not until the early 2000s that efforts began to provide effective protection against malaria to rural populations at national scale.

Three factors made this feasible. The first was a strong platform of evidence, derived from a series of trials in the 1990s, that insecticide-treated nets were extremely cost-effective as a child-survival interventions, for all-cause mortality in young African children. The second was the development, in 2000-4, of long-lasting insecticidal nets (LLINs). These did not need frequent re-treatment with insecticides. The third was the creation of The Global Fund, in 2002, which enabled international donors to invest directly in the scaling-up of proven life-saving interventions like antiretrovirals and LLINs. With the combination of these three factors, it became feasible for the first time for African governments to deliver effective vector control in a sustained manner to the general rural population, even in settings with poor infrastructure.

Between 2004 and 2012, the delivery of LLINs through national-scale mass-campaigns led to rapid scaling up of coverage, and in 2007, the UN Secretary-General announced that the public health community should adopt the goal of "Universal Coverage" with effective anti-malaria interventions. Evaluations showed that the increased coverage achieved by "universal coverage" campaigns was both equitable and effective in reducing child mortality rates even in remote and poor communities.

As a result, in the last two decades, the African population at risk of infection and the age-standardised prevalence of infection in children under 5 have been greatly reduced. The annual number of deaths due to malaria has been reduced by about 50% (fig 3)[30].

Despite some challenges in this progress, including growing insecticide resistance, constrained funding and, most recently, the COVID-19 pandemic (which has resulted in almost 50,000 additional deaths), WHO still has ambitious goals to reduce malaria case incidence and mortality rates by at least 90% by 2030. These gains have led some African countries to start to plan their pathway to the goal of malaria elimination[29]; for example in Nigeria, the "National Malaria Control Programme" is now the "National Malaria Elimination Programme".

c) Current malaria control strategies

The present global malaria control strategy relies primarily on vector control using LLINs and IRS. These are the most powerful and cost-effective currently-available malaria control interventions – in the last two decades they have prevented more than ten million deaths due to malaria – but they have serious limitations. First, in Africa, they are incompletely effective: they can reduce transmission but not prevent completely, because of variability in the behaviour of the vectors. Second, they are based on chemical insecticides, and therefore subject to challenges such as insecticide resistance, which is currently widespread and rapidly-evolving. For these reasons, alternative control methods complementary to existing methods have sometimes been deployed, particularly larval source reduction through environmental management. Larval source management (LSM), targeting the aquatic stages of mosquitoes, has historically been important in some successful malaria elimination campaigns, including some settings where ricefelds were important breeding sites for the local vector *Anopheles* species. These include parts of Europe, Central Asia and China[31]. In these cases, interventions to prevent mosquito-breeding in rice fields are thought to have played an important role not only in the intensive campaigns leading up to elimination, but also and especially post-elimination, during the prolonged stages of 'consolidation' and 'prevention of re-introduction', when other forms of vector control have been withdrawn.

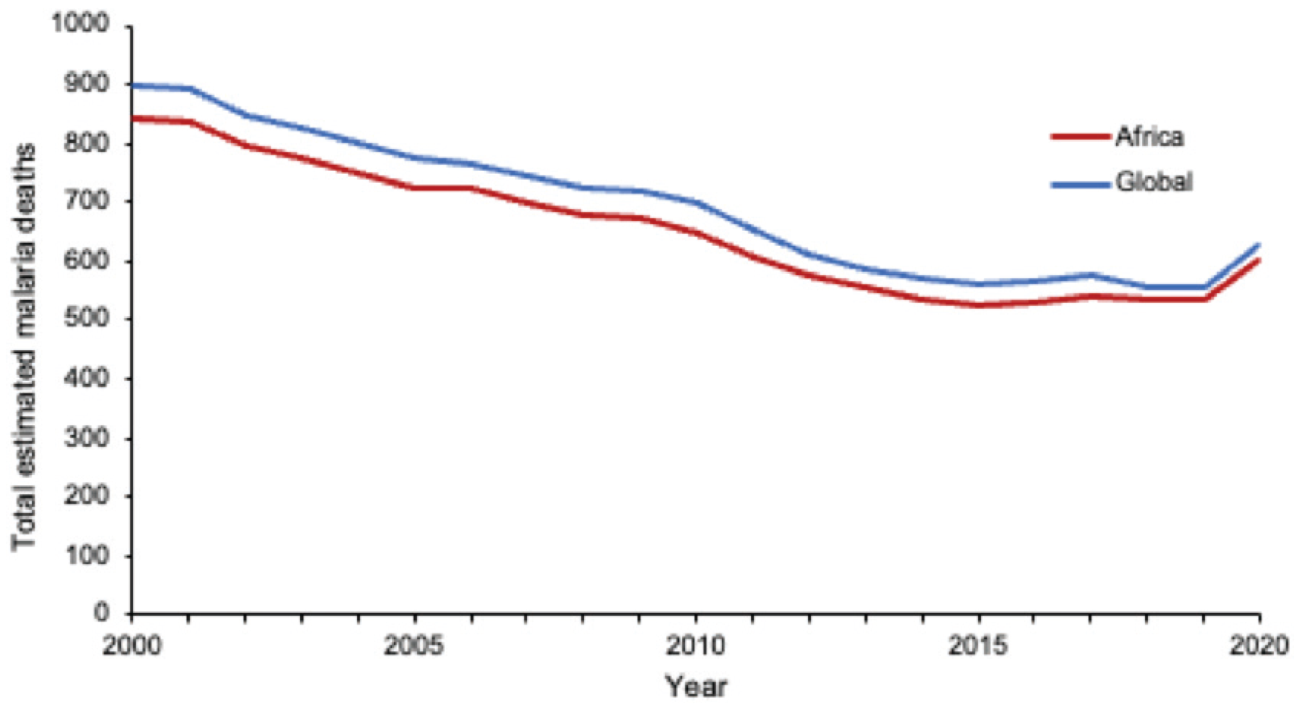

Figure 3. Trends in total estimated malaria deaths, globally and in Africa. Data from WHO29.

3 The impact of rice cultivation on malaria risk

a) The relationship between rice and malaria vectors

Throughout the rice-growing[a] regions in the world, there are local mosquito species that exploit flooded rice fields as breeding sites. However, in most regions, the species of mosquitoes that predominate in rice fields have little or no importance as vectors of malaria, while the main local malaria-vector species have other breeding sites.

There are, however, some important exceptions, where rice fields are a primary breeding site for mosquitoes that are (or used to be) the main local malaria vectors. These places include central China, parts of southeastern Europe and Central Asia, parts of Colombia and Peru, parts of Indonesia and sub-Saharan Africa[32–34]. In some of these regions, e.g. southeastern Europe and mainland China, malaria has already been eliminated, but it remains a major problem in sub-Saharan Africa. The main malaria vector in Africa, *An. gambiae* s.l., is exceptionally efficient at transmitting malaria, and consequently Africa suffers more than 85% of global morbidity and mortality due to malaria. *An gambiae* s.l.[b] is one of those anopheline species that has a strong preference for breeding in rice fields. Hence, from an agricultural perspective, the interactions between rice and malaria are more significant for SSA than they are for regions such as South Asia and the Greater Mekong Region, where there is more rice, but the malaria vector mosquitoes (e.g. *An. culicifacies, An. dirus, An. minimus*) are not so well-adapted to breeding in flooded rice fields.

An. gambiae s.l. prefers to breed in shallow sunlit newly-flooded freshwater pools[33]. Hence the aquatic conditions of rice fields, especially during the early stages of growth, are very suitable for this species [35,36]. *An. gambiae* s.l. is a 'pioneer' species: it is one of the first insects to colonise a newly-created body of suitable water, such as a rice field just after transplantation of the young rice[37]. While the water is still new, and invertebrate aquatic predators have not yet arrived, a large proportion of newly-recruited first-stage mosquito larvae may survive to adulthood (which takes about 1 week). But if the water remains more or less stable for a few weeks, it will be gradually colonised by a variety of aquatic predators, so that an increasing proportion of young larvae will be eaten before they mature. Hence, there is normally a peak in mosquito production in the first 4-5 weeks after transplantation, and the numbers of adults emerging in this first month often comprises more than 50% of the total emerging over the entire growing season [38].

Irrigation schemes are usually installed in settings that were previously natural freshwater wetlands, with their own natural mosquito fauna. However, the transformation from natural wetland to irrigated rice alters the mosquito fauna profoundly, to something close to a monoculture of malaria vectors[39–41]. For example, one study in Western Kenya sampled a diverse mixture of mainly animal-biting non-vector species emerging from natural wetlands, while those emerging from the rice fields were equally numerous but much less diverse, 90% of them being *An. gambiae* s.l. and *An. funestus*.

b) Pre-2005 and the paddies paradox

Over the decades, it has been consistently observed that *An. gambiae* s.l. adults are especially abundant in villages near irrigation schemes[42–45]. There were many expressions of concern about the possibility that these additional mosquitoes might lead to additional malaria in the nearby human population. On this question, however, the evidence was surprisingly mixed. In some places with "unstable malaria transmission", such as Madagascar, a clear and strong association between malaria and rice fields has been reported[46,47]. Elsewhere, and especially in high-transmission parts of mainland Africa, the association between ricefields and malaria was inconsistent and unclear.

For example, in 2001, Ijumba and Lindsay reviewed a set of studies in which malaria outcomes had been measured in rice and nearby non-rice communities[48]. They found that in areas of stable malaria transmission, rice villages tended to have more vectors but less malaria. They called this the "paddies paradox" [48]. Over the next few years, there was a further series of such studies in a range of rice settings in West Africa, co-ordinated by the Africa Rice Center (AfricaRice). This expanded set of observations followed the same paradoxical pattern: the rice villages had substantially larger mosquitoes populations but similar or slightly lower indices of malaria[49].

Various mechanisms were suggested to explain the paddies paradox, but the main idea was that rice brought not only more mosquitoes, but also other beneficial mechanisms that tended to protect against malaria. What mattered was the balance between the harmful effects of the extra mosquitoes and the beneficial effects of these mechanisms. In most cases, the balance seemed to be either neutral or slightly beneficial.

This conclusion has been highly influential. Ever since, agencies promoting irrigated lowland rice production in Africa have used this "paddies paradox" story to provide assurance that despite the mosquitoes, rice development in Africa is not bad for malaria[50].

It is important to look more closely at these proposed underlying mechanisms of the paddies paradox. Three kinds of mechanisms have been suggested, each with some supporting evidence.

The first and most general is that the introduction of rice-growing brings compensating socio-benefits, that is, a wide range of socio-economic and environmental benefits that tend to suppress transmission. These include general benefits such as better roads and housing, and also specific anti-malaria defences, including better access to both commercially-bought mosquito nets and drugs, and to good-quality health services[43,51–55]. Note that these various possible mechanisms are all closely correlated with each other, and in practice it is very difficult to disentangle those that were really acting to suppress malaria from those that were just passively correlated with the process. Note that a key feature of this mechanism is that it depends on inequity: it requires substantial and persistent socio-economic inequalities between rice and non-rice villages.

The second potentially-contributing factor is that in conditions of intense transmission, the prevalence of infection saturates. In such conditions, most people are infected most of the time, and have high levels of partial immunity. When the prevalence of infection approaches 100%, then most infectious bites are falling on people who are already infected. Further increases in transmission can happen, but this merely increases the frequency with which already-infected people receive additional super-infecting bites; it can have little effect on prevalence because that is already near-100%. Hence, prevalence and similar malariological indices become relatively unresponsive to further increases in transmission, while presumably remaining sensitive to factors such as people frequently treating themselves with anti-malarial drugs. Notably, several previous reviews have concluded that an association between rice and malaria in Africa is more likely to be seen in settings with unstable rather than stable transmission[48,49].

Third and last, entomological mechanisms can also produce "paddies paradox" outcomes, with more mosquitoes but less transmission. One of these is general, and perhaps common. This is the idea that when mosquito population densities are very high, density-dependent mechanisms can reduce (or at least set an upper limit to) the vectorial capacity of the population, and hence the ability to transmit the parasite. This could happen through two different ways: (1) a reduction in adult lifespan due to increased competition during larval stage development or (2) a reduction in adult feeding success due to increased mosquito net use (driven by extreme biting nuisance) or, in some places, due to increased cattle numbers near rice fields.

Given these three possible mechanisms, what are the questions that we should consider when updating and re-appraising the studies comparing malaria transmission in rice and non-rice communities? One key issue is that there may

a In this section of the report, we use the word "rice" to refer to irrigated and rainfed lowland rice production systems, and we do not consider upland rice production systems.

b The most widely distributed members of the *An. gambiae* s.l. group of species are *An. gambiae* s.s., *An. coluzzii* and *An. arabiensis*; all three of these breed prolifically in flooded rice. Adaptation to breeding in irrigated rice systems in West Africa is thought to have driven the divergence of *An coluzzi* from *An gambiae* s.s.

have been many changes in these mechanisms, and their relative importance, over the last 15 to 20 years.

Since the 1990s and early 2000s, when the “paddies paradox” studies were conducted, the malaria picture in Africa has changed profoundly. There has been massive scaling up of coverage with modern anti-malaria interventions – vector control, diagnostics and treatment. Coverage has also become much more equitable, within and between communities. As a result, there has been a concomitant and equally widespread decline in the general intensity of transmission, and in the prevalence of malaria infection in the general population. This has two implications for our modern view of the “paddies paradox”.

First, because of the improvements in coverage and equity in coverage, it is no longer safe to assume that non-rice villages have very poor defences against malaria. Presumably, the magnitude of the change depends on which village characteristics were previously giving the differential protection between rice and non-rice villages. For example, LLIN coverage is now remarkably equitable, whereas previously, it was often reported that (untreated) net coverage was very high in rice villages and much lower in non-rice villages (that is, villages with and without irrigated lowland rice fields)[56,57]. On the other hand, there has been no very-large-scale intervention to improve housing quality, and the differentials in housing between rice and non-rice villages may or may not be as strong now as they were before.

Also, and as a consequence of general decline in transmission, there has been a substantial reduction in the fraction of the population at risk exposed to high intensity transmission. Many of those who were previously intensely exposed are now exposed only to low levels of transmission[30]. Hence, if there is a difference in exposure between rice and non-rice villages, we would now expect this to be relatively clearly observable in human malariological indices.

c) Post-2005 and the re-assessment

A systematic review and meta-analysis was conducted to compare the malaria epidemiological and entomological malaria outcomes associated with rice across 53 studies. These studies were conducted from 1971 to 2016, in rural settings in 14 SSA countries in West, Central and East Africa. At the start of this period, coverage with effective modern anti-malaria interventions (such as LLINs) was very low. Starting in the early 2000s, the Global Fund supported a programme of “Scaling-Up for Impact” (SUFI). By 2016, coverage was much higher (around 50%) and by the standard of most public health interventions, coverage was remarkably equitable between rich and poor households. For analysis, these studies were divided into two groups: those carried out before or after 2003, which was about the time when the period of rapid ‘scaling-up’ was initiated.

Epidemiology

23 studies compared malaria infection prevalence in rice and non-rice growing villages and were included in the meta-analysis. In the 16 studies carried out before 2003[c], the overall crude risk ratio[d] [RR] was not significantly different from 1 (crude RR 0.82, 95% confidence interval 0.63–1.06); in other words there was no evidence of an association between rice and malaria risk. In the 7 studies carried out after 2003, by contrast, pooled analysis indicated that the risk of malaria infection was substantially and significantly higher in rice villages (crude RR 1.73, 95% CI 1.01–2.96). These two pooled risk ratios were significantly different from each other.

There was some evidence supporting the idea that in the earlier studies, the malariogenic effects of rice might have been concealed by ceiling effects such as the saturation of prevalence in high-transmission conditions (see above). If these studies are ranked by baseline (no-rice) prevalence (Figure 4B), they appear to fall into three groups. In the few studies with very high (>75%) baseline prevalence, there was almost no difference between rice and non-rice villages. In studies with medium to high (26 to 75%) prevalence, there was the paddies paradox: rice villages had less malaria than non-rice villages. And in most (but not all) of the studies with relatively low (<25%) prevalence, rice villages had more malaria than non-rice villages.

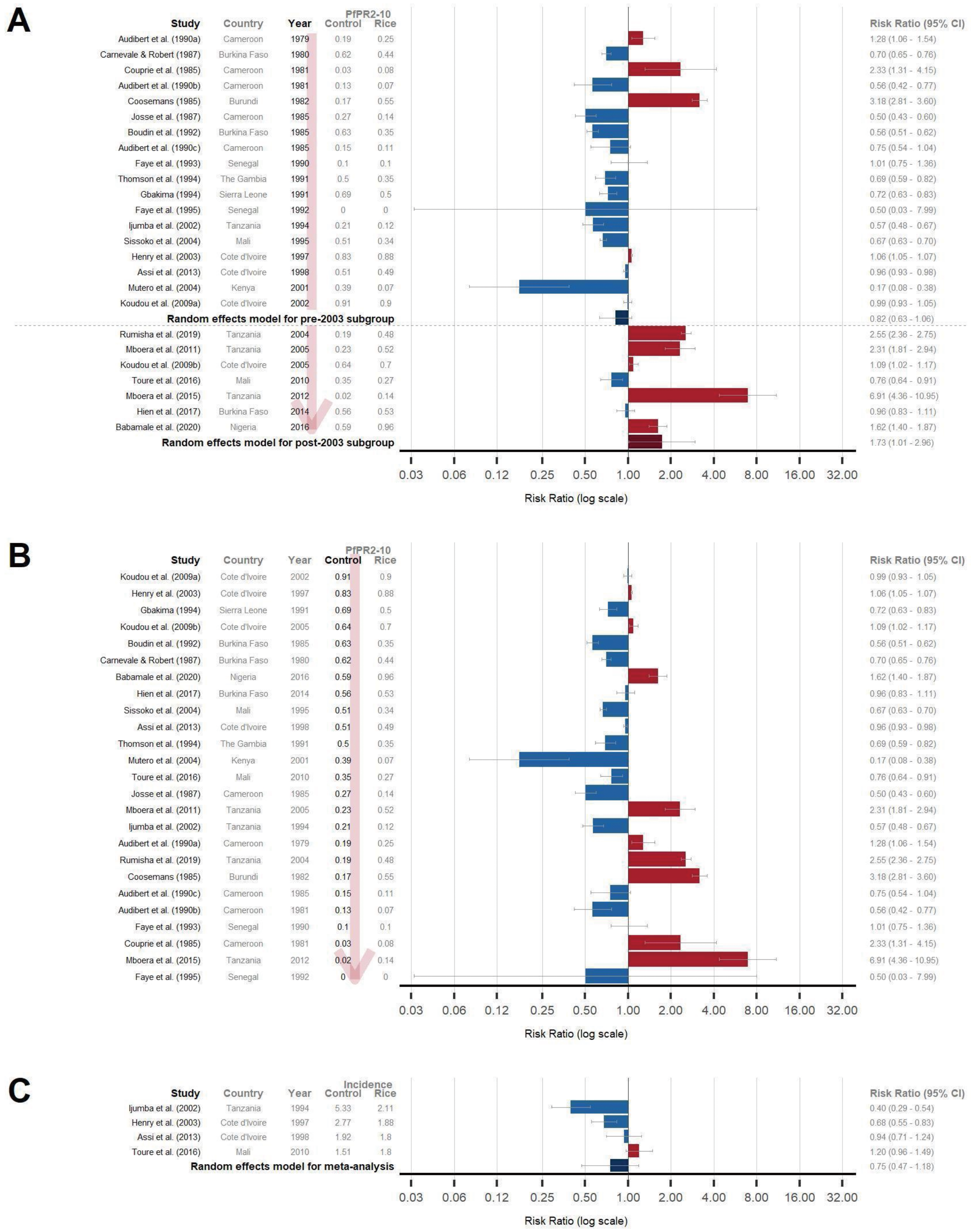

Figure 4. Meta-analyses of the association between rice cultivation and malaria epidemiological outcomes.
Crude risk ratios of malaria infection and their 95% CIs 537 (presented as error bars) are plotted according to (A) subgroup (before and after 2003) and (B) underlying malaria intensity. (C) Crude incidence risk ratios of malaria incidence (per 1000 person-day) and their 95% CIs are plotted according to year of study. Pooled effect estimates of quantitative studies calculated using random-effects models are presented as dark coloured bars at the bottom (of each subgroup). Red bars indicate that, compared to control areas, the epidemiological measure was higher in rice-growing areas, whilst blue bars indicate lower measures in rice.
Chan, K., Tusting, L. S., Bottomley, C., Saito, K., Djouaka, R., & Lines, J. (2022). Malaria transmission and prevalence in rice-growing versus non-rice-growing villages in Africa: a systematic review and meta-analysis. The Lancet Planetary Health, 6(3), e257-e269.

Entomology

We did a similar summary meta-analysis of the 36 studies that collected entomological outcomes, including *Anopheles* human biting rates (HBRs) in rice and non-rice villages. These are summarised in Figure 5.

Overall the abundance of vectors (*An gambiae* s.l.) was much greater in rice than in non-rice villages: overall about seven- or eight-fold (95% CI 2-fold to 21-fold) greater.

Infection (sporozoite) rates tended to be somewhat lower in rice-villages, but by a smaller margin: RR 0.29, 95% CI 0.19–0.46, 17 studies.

Only 3 studies quantitatively reported entomological inoculation rate (EIR) of *An. gambiae* s.l. and their meta-analysis implied that EIR in rice communities was about twice that in non-rice areas (RR 2.03, 95% CI 1.02–4.06, three studies).

Previous reviews have emphasised the idea that at very high population densities, increased competition between mosquitoes may reduce their longevity and hence their vectorial capacity. However, ours seems to be the first meta-analysis of this. Our analysis confirms that the vector populations in rice villages tend to be larger but less infectious (lower sporozoite rates) than those in non-rice villages. However, in most cases, the degree of reduction in sporozoite rates is relatively small, and does not compensate for the major increase in vector numbers. Thus on balance, residents' exposure to biting by infective mosquitoes (EIR) tends to be higher in rice villages (Figure 5).

d) Summary of this section

A The relationship between rice and malaria in Africa matters because:

- Consumption and demand for rice are rapidly growing in Africa; there is ongoing and substantial investment in both expansion and intensification of irrigated lowland rice production.
- Malaria remains a major public health problem in Africa: it kills more than 400,000 people every year in Africa; this represents >80% of the world's malaria burden.

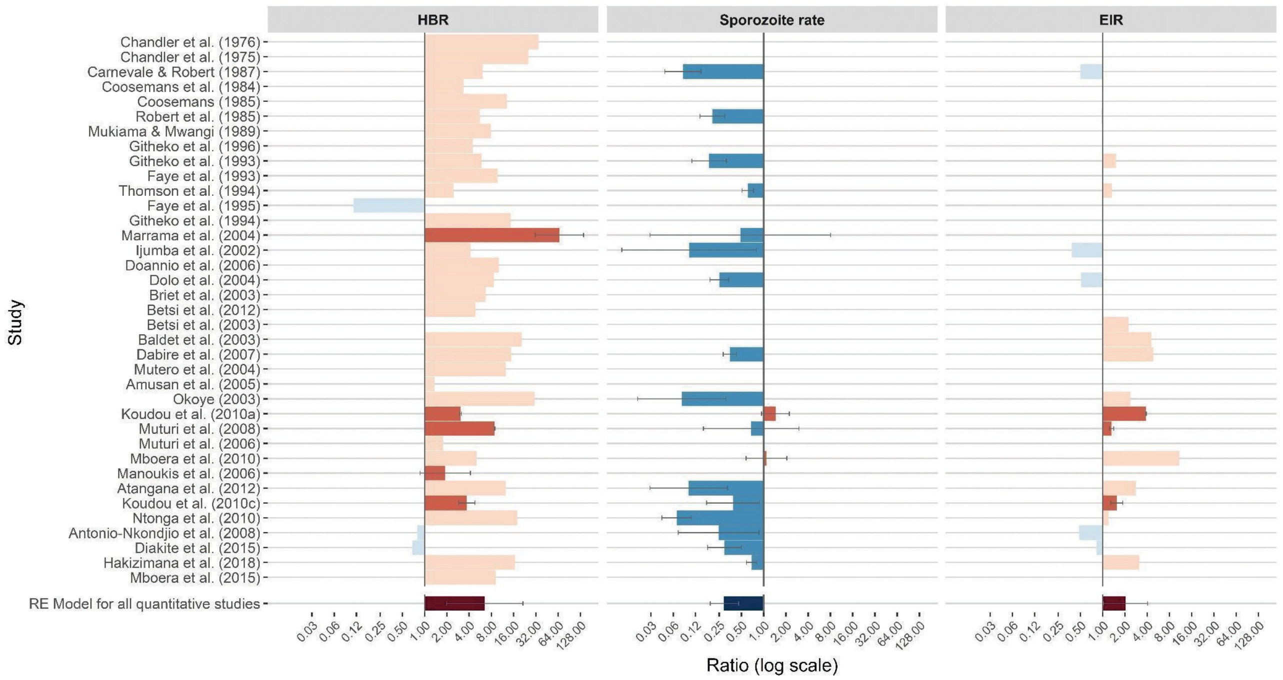

Figure 5. Meta-analyses of the association between rice cultivation and entomological outcomes.
Crude ratio of means (HBR and EIR, where the comparator group was non-rice growing communities), risk ratios (sporozoite rate) and their 95% CIs (only in quantitative studies, presented as error bars) are plotted according to year of study. Red bars indicate that, compared to control areas, the entomological measure was higher in rice-growing areas, whilst blue bars indicate lower measures in rice. Whilst light-coloured bars indicate semi-quantitative studies, solid-coloured bars indicate quantitative studies. Pooled effect estimates of quantitative studies calculated using random-effects models are presented as dark coloured bars at the bottom. Chan, K., Tusting, L. S., Bottomley, C., Saito, K., Djouaka, R., & Lines, J. (2022). Malaria transmission and prevalence in rice-growing versus non-rice-growing villages in Africa: a systematic review and meta-analysis. The Lancet Planetary Health, 6(3), e257-e269.

B Established ideas about irrigated rice and malaria in Africa: "Paddies Paradox"

- In 1995-2005, reviews of the evidence found that irrigated lowland rice is associated with more abundant malaria vector mosquitoes, but not more malaria. This was called "Paddies Paradox".
- This was largely because rice brought not only mosquitoes but also economic and infrastructural development: better housing and health services, more household resources to buy nets and drugs. Thus residents of rice villages were, at that time, much better able to protect themselves against malaria.
- The idea that rice in Africa brings more mosquitoes but not more malaria has been a critical assumption underpinning investments in rice-development in Africa over the last 20 years.

C New evidence that irrigated lowland rice does bring more malaria in Africa

- Our review of recent studies (since 2003) indicates that residents of flooded-rice villages are exposed to more intense malaria transmission, and have a higher prevalence of malaria infection than residents of non-rice villages.
- This is probably because, over the last 20 years, there has been massive scaling-up of coverage with effective anti-malaria interventions.
  - Large-scale surveys show that population coverage with interventions (especially insecticide-treated nets) is generally much more equitable than before. This presumably reduced differentials between rice and non-rice villages in the ability of residents to protect themselves against mosquitoes and malaria.
  - Twenty years ago, there was very intense malaria transmission in much of the lowlands in Africa. In these conditions, infection prevalence is not very sensitive to further increases in transmission because most infectious bites fall upon already-infected people. Because of the general reduction in transmission, many more communities are exposed to intermediate levels of transmission, where population prevalence is very sensitive to changes in transmission.

D The rice-attributable burden of malaria

- Further work will be needed to estimate the "rice-attributable burden of malaria" in Africa, but we already know that it must be substantial.

E This will probably be an emerging problem for malaria in Africa

- Our analysis suggests that the additional malaria risk associated with rice depends on baseline levels of malaria transmission. The effects of irrigated lowland rice on malaria tend to be more conspicuous (and probably larger) in settings with lower background levels of transmission.

- Hence, as malaria declines in Africa, the contribution of irrigated lowland rice production is likely to become more conspicuous and strategically important for national malaria elimination programmes.

- This should not be surprising. Rice fields are an important breeding site for the local malaria vector species in mainland China, parts of Central Asia and southeastern Europe. In these settings, interventions to control vector breeding in rice fields were considered an essential component of the elimination process, and had to be maintained after elimination in order to prevent malaria from returning.

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c Through a sensitivity analysis, the year 2003 was determined to be a relatively robust year to mark the start of the scale-up of malaria interventions.

d Risk ratio, in this instance, measures the relative risk of malaria (prevalence or incidence) among rice communities relative to the risk of malaria among non-rice communities. A risk ratio greater than 1 indicates an increased risk in rice-growing communities, whereas a risk ratio less than 1 indicates a decreased risk in rice-growing communities.

4 Potential interventions to control malaria vector breeding in rice fields

a) The need to produce rice without producing malaria vectors

It appears that nowadays, as sub-Saharan Africa is no longer under "saturation" levels of malaria intensity, the introduction of flooded rice[e] production can bring increased malaria risk. However, preventing rice expansion is not an option, because rice cultivation is a necessity for food security. Thus the cultivation of irrigated rice is necessary, but it currently has an unintended negative side effect: an increase in malaria transmission.

This is clearly an intersectoral problem: a health problem is made worse by an agricultural activity. So which sector should take responsibility for it, or how should responsibility be divided?

The answer to this question would be clearer if there was a simple and decisive intervention on the health side. For example, Dengue, Zika virus and Yellow Fever (YF) are all flaviviruses transmitted between humans mainly by Aedes mosquitoes. Of these three viruses, Yellow Fever is by far the most deadly, and the only one for which we have a vaccine giving 100% life-long immunity. Therefore, for the control of dengue and Zika, public health authorities must rely on vector control interventions that are expensive and only partially effective. Outbreaks of Yellow Fever, by contrast, can be quickly and decisively interrupted by emergency vaccination campaigns.

In the case of malaria, a decisive intervention on the health side does not exist. The world spends more than a billion dollars per year on the delivery of vector control and improved diagnosis/treatment interventions. Good progress has been made, but there is a long way to go. There is a new vaccine, but it gives only partial protection for a number of months; it is unlikely to be a cost-effective way to mitigate the additional malaria transmission caused by irrigated lowland rice.

So what about the interventions we do have, such as LLINs and IRS? Of course, from an agricultural perspective, it is natural to suggest that the problem could be solved by targeting rice villages with these interventions. At first sight, this is an attractive idea, and could be described as re-establishing the Paddies Paradox: villages with rice have more mosquitoes, but those mosquitoes are less able to bite people because the people are better protected.

The problem with this, as an idea, is that its effectiveness depends on inequity: it works only while the non-rice communities are deprived of the benefits given to the rice villages. It is hard to reconcile this, as a strategy, with the overarching principle of equity and the specific policy of universal coverage.

Clearly the problem of malaria is not going to be solved by the agricultural sector. Even the health sector, with remarkably powerful interventions and working at full stretch, can deliver only a partial and not a complete solution. But at the moment, it does seem that the contribution of agriculture is to make the problem worse. So perhaps the role of agriculture is to simply stop being part of the problem, and start being part of the solution.

Therefore, rice-growing methods need to be developed that are unfavourable to mosquitoes but still favourable for the rice. This may require extra effort but it can be done: in many previously malarious countries such as Portugal, Spain, Turkmenistan and China, rice areas were identified as the last hotspots of transmission, and targeted control in the rice fields was often required to achieve malaria elimination and to prevent resurgence[65–68].

e In this section of the report, "rice" refers to irrigated and lowland rice production systems and does not consider upland rice

Some interesting and potentially important comparisons are to be made with greenhouse gases. Like the mosquitoes, these are harmful emissions produced as a side-effect of irrigation, and in both cases, this happens with little or no awareness on the part of the farmers. Rice-development agencies have already acknowledged and started to address the problem of greenhouse gas (GHG) emissions: they now need to acknowledge and start to address the problem of malaria mosquitoes in Africa.

In other words: when rice experts took on the GHG problem, they developed "win-win-win" solutions: methods that (a) suppress GHGs, (b) maintain or increase rice yield, and (c) reduce the need for water. Now, perhaps, "suppressing malaria mosquitoes" must be added to that list: the need is for "win-win-win-win" solutions!

If the R&D task is to develop rice-growing methods that maintain or improve yield, save water, minimise emissions of mosquitoes as well as methane, and (last but not least) will be adopted by farmers, then surely the R&D process must be led by rice experts with technical input from mosquito experts, not the other way round. Farmers are not likely to be interested in rice-growing methods developed by mosquito entomologists.

There is good reason to believe that such solutions are possible. The alternative options for rice cultivation methods are many and diverse, and only a few of them have been studied for their effects on the mosquitoes. These studies, although limited, certainly support the assumption that almost all rice-growing options have more or less substantial effects, positive or negative, on the mosquitoes. We need to study the effects of rice variety (which may affect mosquitoes through effects on shade), methods of levelling and preparation, methods of transplantation, weeding and applying fertiliser. A great deal of more detailed work is needed, but it does seem likely that a combination of modified methods, each of which is partially effective, could add up to effective overall control.

b) Control of mosquitoes in rice fields

Because the relationship between rice and malaria vectors is well-established, malariologists have investigated many different methods of larval source management (LSM) in rice fields since the 1930s. A detailed narrative review by Lacey and Lacey (1990) covers a wide range of these studies, except for chemical control[69]. It also includes studies of techniques that are built into conventional rice cultivation practices, and which only require slight adjustments to effectively reduce vector proliferation in rice paddies. Substantial research attention has been paid to the use of modified water management methods for suppressing mosquito breeding. For example, Keiser et al (2002) prepared a narrative review on the potential of intermittent irrigation in rice fields. They concluded that intermittent irrigation is capable of significantly reducing malaria vector densities, as well as reducing methane emissions and water consumption whilst maintaining good rice yield[70].

As an update to the two reviews written 20-30 years ago, we conducted a systematic review and meta-analysis to assess whether, by and large, riceland LSM (including chemical and biological control) and rice cultivation practices can reduce malaria vector abundance whilst increasing rice yield and reducing water use. Here, we provide a summary of results and their implications.

Most of the relevant studies were conducted in the 1980s and 90s. Most were conducted in North America, Africa, and East and Southeast Asia. There were 16 studies on bacterial larvicides, 10 on chemical larvicides, 8 on fish and 1 each on *Azolla*, copepods and neem. There were 8 studies on modified irrigation, and 7 on land preparation, weeding, water height and plant variety, height and spacing.

Larviciding

Monomolecular surface films (MSF) had mixed results: they produced a modest reduction in anopheline larval numbers in two studies but not in a third.

Chemical larvicides, such as deltamethrin and temephos, were consistently effective, achieving reductions of 56%

to 93% in 8 studies (Figure 6A).

The performance of bacterial larvicides was more variable (Figure 6B). The pooled estimates of effectiveness were good (55% - 72%) but there were some cases where the results were disappointing (<20%). The most effective bacterial larvicides were Bti-based.

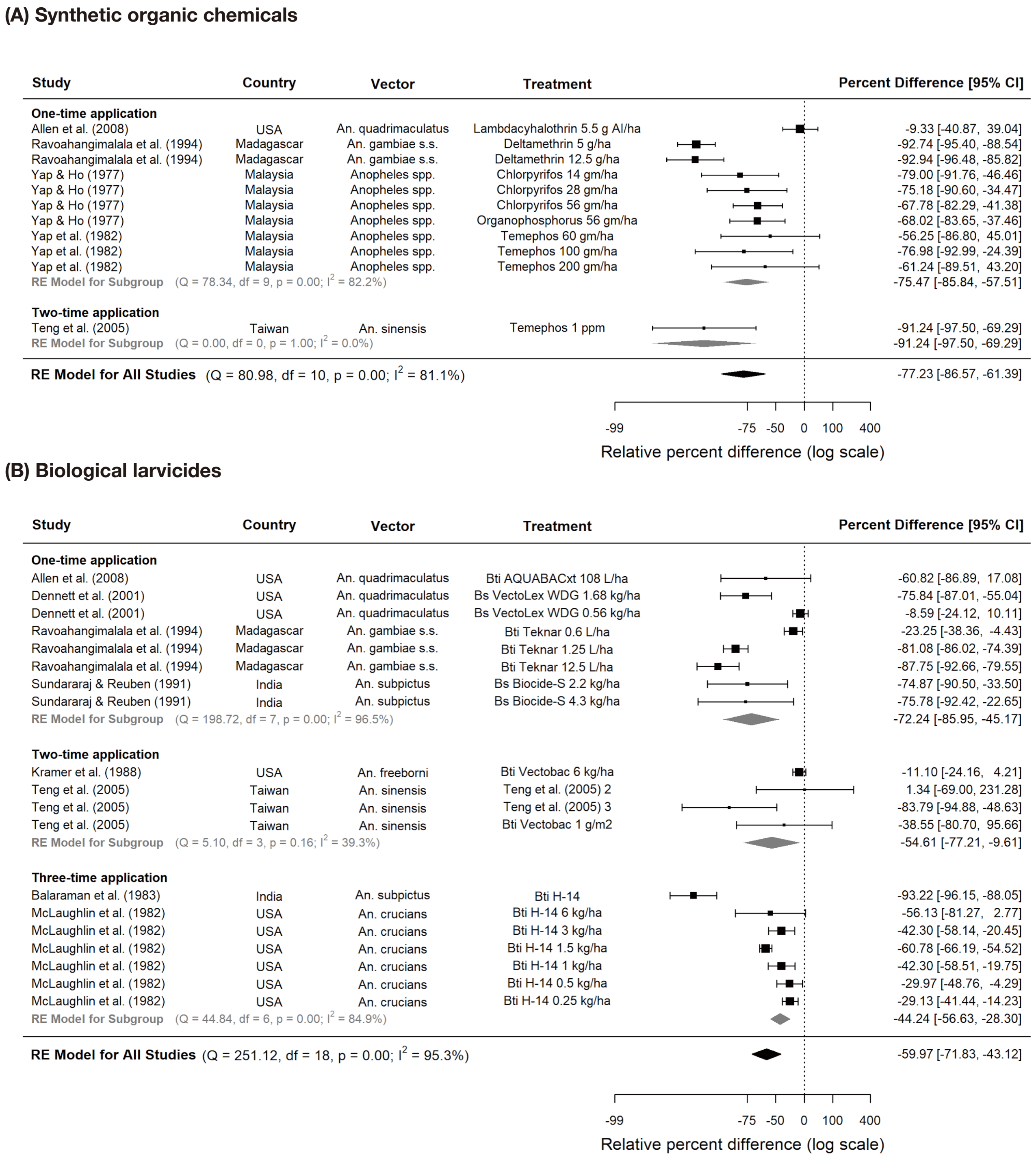

Figure 6. Pooled estimate of the effect of (A) synthetic organic chemicals and (B) bacterial larvicides on Anopheles larval densities in rice fields. Five controlled time series studies on (A) synthetic organic chemicals and eight controlled time series on (B) biological larvicides were included, conducted between years 1975 and 2004. Squares represent the relative effectiveness of individual studies, where square size represents the weight given to the study in the meta-analysis, with error bars representing 95% CIs; diamonds represent the pooled effects from random effects (RE) sub-group and meta-analyses.
Chan, K., Bottomley, C., Saito, K., Lines, J., & Tusting, L. S. (2022). The control of malaria vectors in rice fields: A systematic review and meta-analysis. Under review.

The effects of larvicides were highest immediately after application, but the effect did not persist for more than two weeks. These larvicides mostly had short residual half-lives because they were applied to paddy water which is, in most cases, completely stagnant. Normally, there is a small but continuous process of water loss (through drainage, evapotranspiration and percolation) and replacement through irrigation. In some settings, it is common for each small plot to have a trickle of water in and a trickle of water out. This is important because it means that for sustained control, re-applications have to be repeated at weekly intervals, even with supposedly residual formulations71–74.

Thus, it would be costly and labour-intensive to scale-up a larviciding operation, applying larvicides evenly to every small plot in an entire irrigation scheme. To do this repeatedly at weekly intervals throughout the five months long rice-growing season per year would be even more logistically challenging75,76. Aerial application (including unmanned aerial vehicles), although widely used in the US and Europe, is unlikely to be a feasible delivery system for smallholders in SSA, even in large irrigation schemes72,73,77,78.

Biological control

The simultaneous cultivation of rice and fish was more than 80% effective in reducing the abundance of anopheline immatures, in five trials. Other forms of biological control, including copepods, *Azolla* (mosquito fern) and neem, were not associated with lower numbers of anopheline larvae in rice fields.

Biological control using fish was found to be, in general, somewhat more effective than (chemical, bacterial and MSF) larviciding. The degree of effectiveness was dependent on the fish species and their feeding preferences: surface-feeding, larvivorous species provided better anopheline control than bottom-feeding selective feeders[81,82]. Selecting the most suitable fish for local rice fields is not straightforward; many criteria need to be considered[82–84]. In two studies that accounted for its scalability, fish were well-received by farmers. It was reported that farmers regard fish as contributing to increased yield by reducing weeds and pests and providing fertiliser through excrement[81,85]. This was reportedly also observed in Guangxi, China, where a certain proportion of the field had to be deepened into a side-trench where the fish could take shelter when the fields were drained. Even with this reduction in rice production area, carp rearing still reportedly increased yields by 10% and farmer's income per hectare by 70%[84].

In SSA, irrigated lowland rice-fish farming could be scaled up provided that an inventory of fish species suitable for specific locations is available and that water is consistently available in fields (an important limiting factor in African irrigation schemes)[86]. Lessons can be learnt from successful large-scale rice-fish systems in Asia, where they have served as win-win solutions for sustainable food production and malaria control[87,88].

Unfortunately, none of the eligible studies in this review had included yield or water use as an outcome. Future entomological studies need to measure these critical agronomic variables so that studies of vector control in rice can be understood by, and transferred to, agronomists.

c) Potential vector control within rice cultivation practices

Intermittent irrigation

Compared to continuously flooded fields, water management techniques involving drying intervals were not consistently associated with lower densities of anopheline immatures (Figure 7). When separated into subgroups according to type of drainage, neither active (where water is removed by drainage into canals) nor passive (where water is lost through evaporation or percolation) intermittent irrigation was associated with reduced larval densities but one-time drainage was associated with 24% higher densities (2 studies, Figure 7). When immature abundance was separated into developmental stages, it was revealed that although intermittent irrigation was not associated with significant reductions in early instar larvae, it reduced the abundance of late instars by a pooled estimate of 35% in four studies. In one Kenyan study, draining during transplanting followed by active intermittent irrigation was associated with a 35% reduction in late stage larvae, but a 770% increase in early stage larvae[35].

Overall, there was only limited evidence that intermittent irrigation is effective at reducing late-instar anopheline larvae in rice fields. This finding contrasts with prior reviews, which found mixed results (regardless of larval stage) but emphasised that success was site-specific[70,82,89]. This contrast is presumably due to the inclusion criteria of our systematic review. These excluded some older studies that reported successful anopheline control with intermittent irrigation but lacked either a contemporaneous control arm, adequate replication or adequate differentiation between culicines and anophelines[87,90–94]. It seems, from our review, that intermittent irrigation does not prevent the recruitment of early instars (and in one case, may have encouraged oviposition[35]) but tends to prevent their development into late-stage immatures. This important conclusion is, however, based only on four studies; more evidence is urgently needed where future trials should consider the basic principles of modern trials with adequate replication, controls and differentiation between larval instars and species.

Generally, it is observed that drainage, passive or active, did not reliably reduce overall numbers of mosquito immatures. In India and Kenya, closer inspection revealed that soils were not drying sufficiently, so any stranded larvae were not killed[35,95]. Highlighted by van der Hoek et al. (2001) and Keiser et al. (2002), water management in rice fields is very dependent on the physical characteristics of the soil and the climate and is most suited to places that not only favour rapid drying, but also have a good control of water supply[70,89]. Moreover, repeated drainage, although directed against mosquitoes, can also kill their aquatic predators[96]. Since mosquitoes can re-establish themselves in a newly flooded rice field more quickly than their predators, intermittent irrigation with more than a week between successive drying periods can permit repeated cycles of mosquito breeding without any predation pressure. Its efficacy against malaria vectors is therefore highly reliant on the timing of the wetting and drying periods. Further site-specific research on timing, especially with regards to predator-prey interactions within the rice agroecosystem, is required to find the perfect balance.

Another limitation in intermittent irrigation is that it cannot be applied during the first 2-3 weeks following transplanting, because rice plants must remain flooded to recover from transplanting shock. Unfortunately, this time coincides with peak vector breeding. Thus, other methods of larval control would be required to fill this gap. To agronomists, intermittent irrigation provides benefits to farmers, as it does not penalise yield but significantly reduces water consumption. Nonetheless, farmer compliance seems to be variable, especially in areas where water availability is inconsistent and intermittent irrigation would potentially require more labour[35,97,98]. Moreover, rice farmers doubted their ability to coordinate water distribution evenly amongst themselves, suggesting that there may be sharing issues, as in the "tragedy of the commons"[99]. Instead, they said that they preferred to have an agreed authority to regulate water[95].

Rice cultivation practices other than water management

Studies that examined the effect of rice cultivation practices other than water management methods were scarce. One study in Japan observed that varying rice plant heights were not associated with larval numbers[100]. A study in India showed that plant density, regardless of rice variety, did not affect anopheline larval densities[101]. It was also observed that using herbicides for weed control, compared to no weed control, was associated with 77% higher larval numbers[102]. On the other hand, pesticides were associated with a 76% reduction of anopheline larvae in Indonesia[103]. Different processes in land preparation seemed to affect mosquito numbers: whilst levelling had no effect, rice plots that were minimally tilled were associated with a 65% reduction compared to those with deep tillage (one study)[104].

No general conclusions could be made on the effect on malaria vectors of other rice cultivation practices (apart from water management) because only one study was eligible for each practice. Nevertheless, these experiments on pesticide application, tillage and weed control, as well as another study on plant spacing (not eligible since glass rods were used to simulate rice plants), do illustrate that small changes in agronomic inputs and conditions can have considerable effects on mosquito densities[102,104,105]. Moreover, in partially- or shallowly-flooded plots, the larvae are often concentrated in depressions (usually footprints), suggesting that rice operations which leave or remove footprints (e.g. hand-weeding, drum seeders, levelling) will influence vector breeding[82].

d) Summary of this section

A The task: to reduce the production of adult mosquitoes over the whole rice-growing season

B There are interventions that kill the larvae at the moment of application:

- These are mostly chemical or biological insecticides; they have good immediate effectiveness but no residual effect.
- Frequent re-application would be needed for longer-term control;
- In practice, this is not long-term sustainable: it would be too expensive and too demanding in terms of logistical effort and discipline.

C There are interventions that give longer-term suppression: these are not immediately lethal but reduce the fraction of larvae that survive to adulthood

- These tend to be less immediately effective, but their effect lasts longer.
- Most of these interventions take time to be effective; they cannot prevent the peak of mosquito production 1-5 weeks after transplantation, but they might help to reduce breeding later in the rice-growing season, when the rate of production of adult mosquitoes is still going on, albeit at lower levels because of the presence of predators.

D Effective cover for the whole of the season might be possible using **a combination of these two classes:** short-term insecticidal interventions during the initial 4 to 5 weeks post-transplantation, and suppressive interventions later.

E In any case, it is important that these interventions **must not interfere with the growth of predator populations.** (NB note that the control of rice pests also relies on promoting predators and the same "integrated pest management" principles). In practice this implies a strong preference for bio-insecticides that target mosquitoes, such as *Bti*.

F Other promising ideas include *Azolla* and rice-fish co-culture

- Surprisingly the potential of killifish (*Nothobranchius* spp, very rapid growth, short life-cycle, can survive in dry mud) does not seem to have been investigated.
- The rice-and-fish co-cultivation methods used in southern China (and elsewhere) should be investigated for their potential in Africa

G If the task of controlling mosquito-breeding in rice fields is to be led by the rice experts (whilst being supported by medical entomologists), then entomologists will need **greatly improved methods of monitoring mosquitoes**, i.e. improved methods of counting larvae.

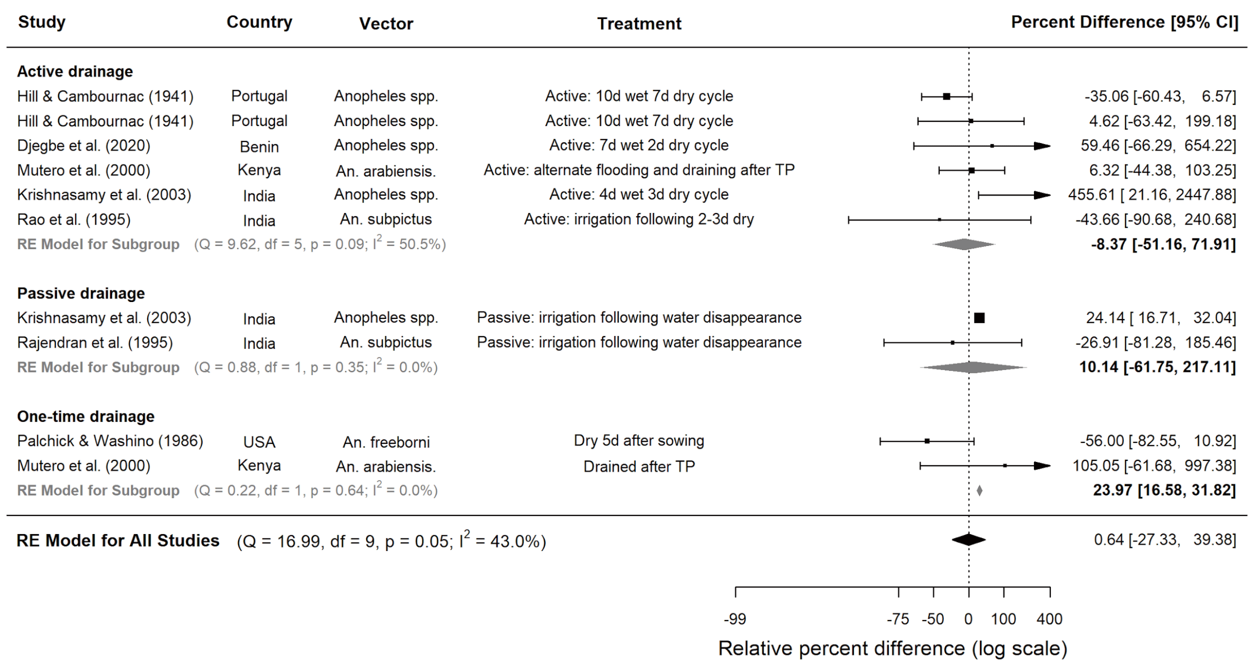

Figure 7. The effect of different intermittent irrigation techniques on larval densities of Anopheles vectors in rice fields. Seven studies were included, conducted between the years 1936 and 2016. Squares represent the relative effectiveness of individual studies, where square size represents the weight given to the study in the meta-analysis, with error bars representing 95% CIs; diamonds represent the pooled effects from random effects (RE) sub-group and meta-analyses.
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5 Overall Summary and Conclusions

a) New evidence on rice and malaria in Africa (paddies paradox)

- The relationship between rice and malaria in Africa has changed: nowadays, irrigated lowland rice production is contributing to the burden of malaria in Africa.
  - In the last 20 years, the massive distribution of effective interventions has reduced malaria transmission, and reduced inequities in intervention coverage.
  - Before this change, the available evidence suggested rice was bringing additional mosquitoes but not more malaria; this was called “paddies paradox” and was probably correct at the time.
  - More recent evidence implies that currently, irrigated lowland rice brings not only more mosquitoes but also more malaria.
- Further analysis suggests that in the future as malaria continues to decline, the associations between rice and malaria will emerge and become stronger. Rice fields are likely to emerge as foci of remnant transmission and become more conspicuous as an obstacle to elimination.

b) The strategic response

- These findings should NOT be interpreted as an inevitable trade-off between health and food and nutrition security, or as a reason to delay the expansion and intensification of rice in Africa.
- In fact the trade-off is not inevitable.
  - Modified methods of rice-cultivation can minimise the number of mosquitoes emerging from rice fields.
  - It seems likely that with further research, methods can be developed that will not only reduce mosquitoes but also improve yield and be attractive to farmers.
  - Achieving such co-benefits should become a prioritised element within rice development research in Africa. This can follow the example of reducing greenhouse gas (GHG) emissions from rice fields; researchers successfully developed methods to address this challenge. It might even be possible to develop methods that can control emissions of both GHG and mosquitoes.
- More anti-malaria interventions – more nets and drugs – may be part of a short-term response, but they do not represent a sustainable long-term solution for the pathway to malaria elimination.
- Using current cultivation methods, the additional vectors from rice fields will always be a harmful unintended side effect of rice-growing in Africa. Conversely, the suppression of mosquito-breeding using modified rice-cultivation methods would be a highly beneficial intended side-effect.
- Thus the development of irrigated rice in Africa should continue, but accompanied by a comprehensive programme of research to develop such anti-mosquito methods of growing rice.

c) Priority intervention areas

- The best approach is probably to integrate the objective of mosquito control as fully as possible in the work of rice-research & development agencies. It means adding the monitoring of mosquito-breeding into every development project working for expansion and intensification of rice cultivation.

- This raises a methodological issue: current methods of counting larvae are hopelessly labour-intensive and demanding; rice field workers will simply not use them. There are some promising ideas for new methods and these need to be developed.
- A multi-centre approach is needed. Suppressing mosquitoes will require different methods in different places. The numbers of adult mosquitoes emerging is always very variable and sensitive to growing conditions. Alternative rice-growing methods (including tilling, levelling, sowing, fertilizing and weeding) can all have large effects on mosquito numbers. Most of these effects have not been adequately investigated.
- Previous work suggests that optimal effectiveness may be achieved with a complementary mix of interventions, some appropriate for the first few weeks of the rice-growing season and others for the later parts of the season.
- Potential win-win interventions should also be explored - rice interventions that aid climate change adaptation and mitigation may provide co-benefits to health.
- More social science studies investigating the views and perspectives of rice farmers on mosquitoes and potential rice interventions are required. Since smallholder farmers constitute most of the rice production in sub-Saharan Africa, cooperation from all farmers in the same irrigation scheme or same wetland must be required for any riceland mosquito control strategy to succeed. Thus, methods to advocate collective participation of all farmers must be explored.

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7 Biography

Name: Jo Lines

Position: Professor of Vector Biology and Malaria Control

Affiliation: the London School of Hygiene & Tropical Medicine.

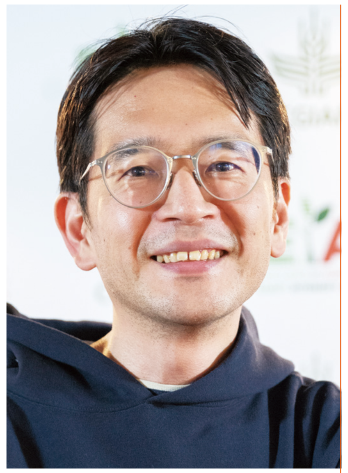
Profile:
I work on practical methods for the control of malaria mosquitoes. After training in evolutionary genetics and then medical entomology, I lived and worked in a small town in Tanzania, working with colleagues to develop methods for the study of vector control interventions, especially insecticide-treated nets, and helping to build a field research station. Over the years, I've been involved in collaborative research in Southeast Asia, China and Latin America, and I've worked as a consultant in support of national malaria control programmes, and in the design and evaluation of malaria control projects. From 2008 to 2011, I was Coordinator of the Vector Control Unit of the World Health Organisation's Global Malaria Programme in Geneva, where I initiated and led the development of several still-current set of WHO policy recommendations, especially the Global Plan for Insecticide Resistance Management. Over the years, my research has gradually become more multi-disciplinary and inter-sectoral. My current research addresses two main issues: the insecticide resistance arms race with Africa vectors, and the growing problem of "man-made malaria" in anthropogenic landscapes.

Name: Kallista Chan

Position: Research Uptake Manager

Affiliation: RAFT Consortium, London School of Hygiene and Tropical Medicine

Profile:
With a background in infectious disease epidemiology and medical entomology, I have a special interest in vector-borne diseases and their control. I am particularly interested in the multisectoral nature of vector-borne diseases such as the influence of landscape and agriculture on risk and potential control. I am currently a PhD candidate at the London School of Hygiene and Tropical Medicine, where I am exploring methods of growing rice without growing malaria vectors.
In collaboration with AfricaRice and International Rice Research Institute, the PhD aims to identify potential agriculture and health co-benefits in improved or novel rice cultivation techniques such as alternate wetting and drying irrigation.

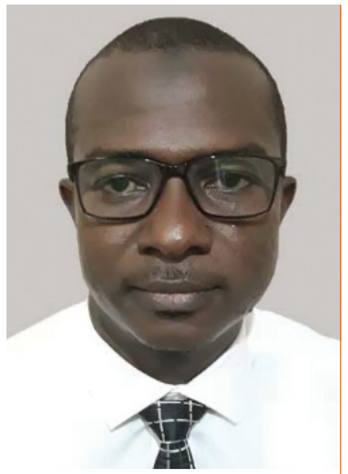


Name: Kazuki Saito

Position: Principal scientist

Affiliation: Africa Rice Center

Profile:
I am an agronomist employed by the Africa Rice Center, based in Côte d'Ivoire. I have >20 years of research experience in Asia (2000-2005 as part of my MSc and PhD studies) and sub-Saharan Africa (2006-present). I am also research fellow in Japan International Research Center for Agricultural Sciences (JIRCAS) (2017-present), and part-time lecturer for Tokyo University of Agriculture and Technology (2018-present). My works have focused on yield gap assessment, diagnostic surveys, integrated management practices, decision support tool on nutrient management practices, farming systems research, and improvement of yield potential and abiotic/biotic stress resistance in rice. I have authored and co-authored more than 100 scientific papers in peer-reviewed journals. I received my PhD degree in Agriculture from Kyoto University,
Japan on 'Description, constraints and improvement of slash-and-burn upland rice production systems in northern Laos'. I was awarded the Louis Malassis International Scientific Prize for Young Promising Scientists in 2015.



Name: Ali Ibrahim

Position: Systems Agronomist

Affiliation: Africa Rice Center

Profile:
I have been working for Africa Rice Center as Systems Agronomist since 2019. My current research focuses on developing, testing, and disseminating sustainable intensification and diversification options in irrigated rice farming systems for improving livelihoods, nutrition and resilience of rural communities and smallholder farmers in sub-Saharan Africa. Prior to joining AfricaRice, I worked for OCP Africa as agronomist to develop and implement site-specific nutrient management practices for sustainable crop production. I have authored and co-authored more than 20 papers in peer-reviewed journals. I received my PhD degree in Integrated Soil Fertility Management from Kwame University of Science and Technology, Ghana in 2015. I received the President's International Fellowship Initiative (PIFI) Postdoctoral Researcher Award from Chinese Academy of Sciences (CAS) in 2016 and the Emerging Leader for African Agricultural Transformation (ELAAT) Award in 2021, which was sponsored by OCP Northern America and the American Society of Agronomy.

About Malaria No More Japan

Malaria No More Japan was established in 2012 as the Japanese branch of the U.S.-based Malaria No More and is the only certified non-profit organization specializing in malaria in Japan (acquired non-profit status in 2013, certified as a certified non-profit organization in 2015).

Malaria No More group work to achieve our vision, "To be zero-malaria world in our lifetime". To achieve this vision, Malaria No More Japan has committed policy advocacy, communication, and promotion of partnerships.

Official name:	Malaria No More Japan (NPO)
Representative:	Prof. Dr. Takahiro Shinyo Dean of the Integrated Center for UN and Foreign Affairs Studies, Kwansei Gakuin University, and Trustee of Kwansei Gakuin. He has served as Director of the Global Issues Department of the Ministry of Foreign Affairs, Ambassador Extraordinary and Plenipotentiary at the Permanent Mission of Japan to the United Nations, and Ambassador Extraordinary and Plenipotentiary of Japan in the Federal Republic of Germany. After serving as Vice President of Kwansei Gakuin University, he assumed his current position in June 2018.
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