Effect of Rice Cultivation on Malaria Transmission in Central Kenya

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Abstract. A 12-month field study was conducted between April 2004 and March 2005 to determine the association between irrigated rice cultivation and malaria transmission in Mwea, Kenya. Adult mosquitoes were collected indoors twice per month in three villages representing non-irrigated, planned, and unplanned rice agro-ecosystems and screened for blood meal sources and *Plasmodium falciparum* circumsporozoite proteins. *Anopheles arabiensis* Patton and *An. funestus* Giles comprised 98.0% and 1.9%, respectively, of the 39,609 female anophelines collected. Other species including *An. pharoensis* Theobald, *An. maculipalpis* Giles, *An. pretoriensis* Theobald, *An. coustani* Laveran, and *An. rufipes* Gough comprised the remaining 0.1%. The density of *An. arabiensis* was highest in the planned rice village and lowest in the non-irrigated village and that of *An. funestus* was significantly higher in the non-irrigated village than in irrigated ones. The human blood index (HBI) for *An. arabiensis* was significantly higher in the non-irrigated village compared with irrigated villages. For *An. funestus*, the HBI for each village differed significantly from the others, being highest in the non-irrigated village and lowest in the planned rice village. The sporozoite rate and annual entomologic inoculation rate (EIR) for *An. arabiensis* was 1.1% and 3.0 infective bites per person, respectively with no significant difference among villages. Sporozoite positive *An. funestus* were detected only in planned rice and non-irrigated villages. Overall, 3.0% of *An. funestus* samples tested positive for *Plasmodium falciparum* sporozoites. The annual EIR of 2.21 for this species in the non-irrigated village was significantly higher than 0.08 for the planned rice village. We conclude that at least in Mwea Kenya, irrigated rice cultivation may reduce the risk of malaria transmission by *An. funestus* but has no effect on malaria transmission by *An. arabiensis*. The zoophilic tendency of malaria vectors in irrigated areas accounts partly for low malaria transmission rates despite the presence of higher vector densities, highlighting the potential of zooprophylaxis in malaria control.

INTRODUCTION

Irrigated agriculture increases crop production by enabling the reclamation of arid and sub-arid lands, extending the crop-growing season, and reducing crop failure. For this reason many countries in sub-Saharan Africa have developed irrigation projects to provide food security, improved diet and increased income for a rapidly growing population.[1] Unfortunately, water-related projects may aggravate the problem of mosquito-borne disease by increasing the number of larval habitats and extending the duration of transmission season.[2] In particular, rice cultivation has received greater attention in Africa because it comprises one-third of all irrigated crops and requires flooded conditions that provide ideal habitats for at least 140 mosquito species worldwide.[3]

In general, irrigated areas support higher densities of malaria vectors than adjacent non-irrigated areas and the effect on malaria transmission and prevalence may vary depending on local ecologic conditions. In Sri Lanka, introduction of the Mahaweli Irrigation Scheme resulted in a five-fold increase in malaria incidence among the local population.[4] Introduction and expansion of acreage under cotton, wheat, sorghum, and vegetable irrigation led to serious outbreaks of malaria in Gezira-Managil system in the Nile River valley.[5] Development of dams for irrigation also increased malaria incidence in Benoue Valley, Cameroon,[6] and Tigray, Ethiopia.[1] In Rusizi Valley, Burundi vectorial capacity of *Anopheles gambiae* Giles *s.l.* was 150 times higher in the rice irrigation scheme than in adjacent cotton growing areas.[7] In contrast, irrigated

rice cultivation in Mali was associated with a reduction in the annual incidence of malaria[8] and a 10-fold reduction in the sporozoite rate than was found in adjacent non-irrigated areas.[9] In Lower Moshi Tanzania, malaria transmission and prevalence was significantly lower in irrigated than in neighboring sugarcane and cotton growing areas.[10,11] Githeko and others[12] reported that the sporozoite rate of *An. gambiae s.l.* was five times lower in the Ahero rice scheme than in the neighboring sugar cane growing area. The introduction of irrigated rice cultivation in the Senegal River delta did not alter malaria transmission.[13] Collectively, these findings indicate that the relationship between irrigated rice cultivation and malaria transmission is complex and can only be understood through site-specific evaluation of local vectors and underlying ecologic and epidemiologic factors.

The Mwea Rice Irrigation Scheme is the largest of its kind in east Africa, covering an area of approximately 13,640 hectares. Recent studies have shown that the densities of *An. arabiensis* Patton are higher within the scheme than in the neighboring non-irrigated areas, and *An. funestus* Giles is more abundant in non-irrigated areas.[14,15] Surprisingly, there has been no entomologic study to assess the impact of rice cultivation on malaria transmission in this area. Because malaria prevalence was shown to be lower within the scheme than in neighboring non-irrigated areas,[14] it was our hypothesis that rice cultivation reduced the risk of malaria transmission in the area. We tested this hypothesis by comparing the risk of malaria transmission in three agro-ecosystems with different patterns of land use.

MATERIALS AND METHODS

Study sites. The study was conducted in three villages (Mbuinjeru, Kiamachiri, and Murinduko) located in Mwea

division, Kirinyaga District, 100 km northeast of Nairobi, Kenya. The study sites have been described in detail by Muturi and others.[15,16] The study area has two annual rainfall seasons; the long rains in April–May and the short rains in October–November. Annual average rainfall is 950 mm. The average maximum temperature range is 16–26.5°C, and average relative humidity varies from 52% to 67%. *Anopheles arabiensis* is the dominant *Anopheles* species,[15] the main vector of malaria,[17] and the only sibling species of *An. gambiae s.l.* present within the Mwea Rice Scheme on the basis of cytotaxonomic[17] and ribosomal DNA polymerase chain reaction studies.[18,19] The prevalence of malaria in Mbuinjeru, Kiamachiri and Murinduko among children ≤ 9 years of age is 0%, 17%, and 54%, respectively.[14]

Mbuinjeru is within the Mwea Irrigation Scheme and more than 75% of the village land is under rice cultivation. Farmers in this village follow a defined rice cropping cycle as determined by the National Irrigation Board (planned rice cultivation). The typical rice cultivation cycle includes a land preparation–transplanting period (July–August), a growing period (August–November), and a post-harvest period (November–December). The second crop if planted is cultivated prior to the long rainy period between January and May. Human habitation occupies the remaining area with less than 10% used for vegetables and bananas.

Kiamachiri is immediately outside the scheme with approximately 20% of the area under rice cultivation. In this village, individual farmers decide their own cropping cycle depending on water availability. Consequently, rice is grown throughout the year as long as water is available in Gakungu River to irrigate the paddies (unplanned rice cultivation). The remaining 80% of the land is mainly planted with maize, beans, and bananas.

Murinduko is situated approximately 15 km from the scheme and is generally a non–rice-growing village mainly because of its hilly topography that renders much of the area (approximately 90%) unsuitable for rice cultivation. However, limited rice growing activity (< 5% of the total area) is conducted along one major river valley that runs along the edge of the village. Maize, beans, and bananas are the main crops cultivated but only on subsistence scale.

Demographic and meteorologic data. A pre-study population census was done to provide basic human demographic data. This was accomplished by a house-to-house visit to determine the number of people residing in each village and family size. In addition, a census of domestic animals was also completed. This information was used to establish the human to cattle ratio. Before gathering the above information, the household head was briefed on the purpose of the study and his or her consent to provide the information requested.

The meteorologic data collected during the study period included rainfall, temperature, and relative humidity. Rain gauges (Tru-Chek®; Rain Gauge Division, Edwards Manufacturing Co. Albert Lea, MN) were placed in each of the three villages and rainfall was recorded daily throughout the study period from April 2004 to March 2005. Temperature and relative humidity for each of the village was obtained using temperature and relative humidity data loggers (Onset Computer Corporation, Bourne, MA).

Mosquito sampling and processing. Adult mosquitoes were sampled twice per month between April 2004 and March 2005. The collections were done in 30 randomly selected houses between 7:00 AM and 11:00 AM using the pyrethrum spray catch (PSC) technique.[20] In each study site, the location of each homestead was categorized as center or periphery and equal numbers of houses were selected from each category. Any homestead less than 15 meters from the village perimeter was classified as being at the periphery of the village. Mosquitoes were transported from the field to the laboratory where they were identified to species by morphologic characteristics.[21,22] Each mosquito was scored as unfed, blood-fed, semi-gravid or gravid by visual abdominal examination under a dissecting microscope. The guts of a representative sample of blood fed anophelines collected at each village were analyzed using an enzyme-linked immunosorbent assay (ELISA)[23] to identify the relative proportion of adult mosquito population feeding on humans and cattle. The heads and thoraces of another sample comprising all classes of mosquitoes (unfed, blood-fed, semi-gravid and gravid) was analyzed by ELISA for *Plasmodium falciparum* circumsporozoite proteins.[24]

Entomologic indices. The human blood index (HBI) was determined as the proportion of blood-fed mosquitoes that had fed on humans of the total number tested. The feeding success was determined as the proportion of blood fed and semi-gravid mosquitoes in the total proportion presumed to have attempted to feed (all mosquitoes except gravids).[25] The sporozoite index for a given species was calculated as the proportion of females carrying infective sporozoites in the head-thorax of the total number tested. The human biting rate was derived as the product of blood fed and semi-gravid females per person per night and the human blood index. The product of human biting rate and sporozoite index yielded the entomologic inoculation rate (EIR), a standard measure of transmission intensity.[26] Githeko and others[27] did not find any evidence of early exophily by rice land *An. arabiensis* and *An. funestus*. We therefore considered mosquito samples from PSC to be relatively good estimates of human biting rates and EIR.

Data analysis. Data were analyzed using the SPSS version 11.5 statistical package (SPSS, Inc., Chicago, IL). Mosquito densities and biting rates were log-transformed before analysis to normalize the data. Analysis of variance was used to compare the differences in mosquito densities, human biting rates, and EIR among villages and the means were separated by Tukey test. The chi-square test was used to compare differences in feeding success and sporozoite rates of mosquito species among villages.

RESULTS

Demographic data. The ratio of humans to cattle in both planned (Mbuinjeru) and unplanned (Kiamachiri) rice agroecosystems was 5:1 compared with a 12:1 in the non-irrigated village (Murinduko). The total precipitation for the period April 2004 to March 2005 was 810.4 mm, 679.8 mm, and 803.1 mm, for the planned, unplanned and non-irrigated agroecosystems, respectively. The rainfall pattern was bimodal with peaks in April and November. The average daily temperature for this period was 22.9°C and the average relative humidity was 71.0%.

Species composition and abundance. A total of 39,609 female anophelines were collected between April 2004 and March 2005. *Anopheles arabiensis* was the dominant species

comprising 98.0% of the total collection, followed by *An. funestus* at 1.9%. The remaining 0.1% was composed of *An. pharoensis* Theobald, *An. maculipalpis* Giles, *An. pretoriensis* Theobald, *An. coustani* Laveran, and *An. rufipes* Gough. The mosquito species diversity and abundance for the three study sites has been described in detail elsewhere.[15]

Vector density, feeding success, human blood index, and human biting rates. The overall indices of malaria transmission at the three study sites are shown in Table 1. The mean ± SE number of *An. arabiensis* per person per night was 10.76 ± 0.60 in the planned rice agro-ecosystem (Mbuinjeru), which was two-fold higher than in the unplanned rice agro-ecosystem (Kiamachiri; 5.36 ± 0.45) and 12-fold higher than in the non-irrigated agro-ecosystem (Murinduko; 0.91 ± 0.09). Tukey's honestly significant differences test showed that each agro-ecosystem differed significantly from the others (F = 85.33, degrees of freedom [df] = 2, 71, $P < 0.001$). The mean ± SE number of *An. funestus* per person per night in the planned and unplanned rice agro-ecosystems was 0.04 ± 0.00 and differed significantly from the value of 0.27 ± 0.01 for the non-irrigated agro-ecosystem (F = 5.054, df = 2, 71, $P < 0.01$). The average feeding success for *An. arabiensis* and *An. funestus* was 0.63 and 0.62, respectively, with no significant difference among agro-ecosystems. The human blood index of *An. arabiensis* was significantly higher in the non-irrigated agro-ecosystem (0.50) than in the planned (0.09) and unplanned (0.12) rice agro-ecosystems (χ^2 = 158.361, df = 2, $P < 0.001$). For *An. funestus*, the human blood index was 0.72 in the non-irrigated site, 0.27 in the unplanned rice site, and 0.11 in the planned rice site. This difference was significant (χ^2 = 26.438, df = 2, $P < 0.001$). In the non-irrigated agro-ecosystem, *An. funestus* was more anthropophilic than *An. arabiensis* (χ^2 = 8.555, df = 1 $P < 0.01$) but the difference was not significant for the other sites. The blood meals for *An. coustani* (n = 14), *An. maculipalpis* (n = 2), and *An. rufipes* (n = 2) were of bovine origin, but *An. pharoensis* (n = 7) and *An. pretoriensis* (n = 1) were not tested for blood meal sources because all the adults collected were unfed. The mean ± SE human biting rate per person per night for *An. arabiensis* in the non-irrigated site was 0.46 ± 0.02 and was significantly lower than the values of 0.97 ± 0.12 in the planned rice site and 0.64 ± 0.05 in the unplanned rice site (F = 39,421, df

= 2, 71, $P < 0.01$). Similar values for *An. funestus* were 0.004 ± 0.00 and 0.011 ± 0.00 in the planned and unplanned rice sites, respectively, and these values were significantly lower than the value of 0.20 ± 0.01 SE in the non-irrigated site (F = 10.036, df = 2, 71, $P < 0.01$).

Sporozoite rate and EIR. The overall sporozoite rates and EIR values are shown in Table 1. Sporozoite-positive *An. arabiensis* samples were detected in all the three agro-ecosystems (range = 0.72–1.73) and the observed difference was not statistically significant (χ^2 = 2.624, df = 2, $P > 0.05$). In the planned rice and non-irrigated sites, sporozoite-positive *An. arabiensis* was observed in December and March whereas in the unplanned rice site, they were detected in October and December. Sporozoite-positive *An. funestus* were only detected in planned rice (in December) and non-irrigated sites (in January and February) (Table 2). The calculated difference between the two sites was not statistically significant (χ^2 = 1.014, df = 1, $P > 0.05$). None of the other species (*An. pharoensis*, *An. coustani*, *An. maculipalpis*, *An. pretoriensis*, and *An. rufipes*) were positive for *P. falciparum* circumsporozoite proteins.

The annual EIR for *An. arabiensis* ranged between 2.5 and 4.1 infective bites per person with no statistically significant difference among sites (F = 0.401, df = 2, 33, $P > 0.05$). Conversely, the annual EIR for *An. funestus* in the non-irrigated site was 26-fold higher than the corresponding value in the planned rice site (F = 8.082, df = 2, 33, $P < 0.01$). None of the 92 individuals of this species collected in the unplanned rice site was positive for *P. falciparum* circumsporozoite proteins (Table 1). The monthly distribution of EIR for both species was similar to the sporozoite index (Table 2).

DISCUSSION

Based on results of adult mosquito densities and human biting rates, *An. arabiensis* was strongly associated with rice cultivation and *An. funestus* was common in the non-irrigated agro-ecosystem. Even among irrigated rice agro-ecosystems, significantly higher densities of *An. arabiensis* were collected in the planned rice agro-ecosystem than in the unplanned rice agro-ecosystem. This was expected because the area under

TABLE 1
Entomologic indices of *Anopheles arabiensis* and *An. funestus* in non-irrigated and planned and unplanned rice agro-ecosystems in Mwea, Kenya*

Species	Transmission indices	Mbuinjeru (planned)	Kiamachiri (unplanned)	Murinduko (non-irrigated)
An. arabiensis	Total collected	26,399	10,983	1,446
	Mean no./person/night†	10.76[a]	5.36[b]	0.91[c]
	Feeding success	0.63	0.60	0.66
	Human blood index†	0.09[a] (n = 812)	0.12[a] (n = 334)	0.50[b] (n = 131)
	Bovine blood index	0.78	0.75	0.44
	Human biting rate/night†	0.97[a]	0.64[a]	0.46[b]
	Sporozoite rates (%)	0.72 (n = 832)	1.73 (n = 347)	1.5 (n = 133)
	Annual EIR	2.55	4.06	2.50
An. funestus	Total collected	87	92	560
	Mean no./person/night†	0.04[a]	0.04[a]	0.27[b]
	Feeding success	0.60	0.59	0.68
	Human blood index†	0.11[a] (n = 19)	0.27[b] (n = 11)	0.72[c] (n = 65)
	Bovine blood index	0.74	0.64	0.09
	Sporozoite rates (%)	5.26	0.00	3.08
	Human biting rate/night†	0.004[a]	0.011[a]	0.197[b]
	Annual EIR†	0.08[a]	0.00	2.21[b]

* EIR = entomologic inoculation rate. Values with different superscript letters within a column are significantly different at $P < 0.05$.
† Indicates indices of malaria transmission in which significant differences were observed.

Monthly entomologic parameters of *Anopheles arabiensis* and *An. funestus* in non-irrigated and planned and unplanned rice agro-ecosystems in Mwea, Kenya*

Site	Month and year	An. arabiensis				An. funestus			
		Density	HBR	SP	EIR	Density	HBR	SP	EIR
Mbuinjeru	Apr 2004	4.69	0.11	0.00	0.00	0.00	0.00	0.00	0.00
	May 2004	4.33	0.20	0.00	0.00	0.25	0.03	0.00	0.00
	Jun 2004	2.87	0.08	0.00	0.00	0.25	0.03	0.00	0.00
	Jul 2004	3.51	0.12	0.00	0.00	0.38	0.04	0.00	0.00
	Aug 2004	7.99	0.75	0.00	0.00	0.67	0.07	0.00	0.00
	Sep 2004	26.10	1.45	0.00	0.00	0.75	0.08	0.00	0.00
	Oct 2004	12.66	1.52	0.00	0.00	0.00	0.00	0.00	0.00
	Nov 2004	14.25	1.24	0.00	0.00	0.50	0.05	0.00	0.00
	Dec 2004	9.12	0.95	0.06	0.06	0.67	0.07	0.14	0.01
	Jan 2005	24.38	6.04	0.00	0.00	0.67	0.07	0.00	0.00
	Feb 2005	9.82	3.93	0.00	0.00	0.00	0.00	0.00	0.00
	Mar 2005	5.79	0.46	0.01	0.01	0.13	0.01	0.00	0.00
Kiamachiri	Apr 2004	7.04	2.01	0.00	0.00	0.36	0.10	0.00	0.00
	May 2004	2.70	0.12	0.00	0.00	0.78	0.21	0.00	0.00
	Jun 2004	1.67	0.31	0.00	0.00	0.53	0.15	0.00	0.00
	Jul 2004	5.05	0.00	0.00	0.00	0.47	0.13	0.00	0.00
	Aug 2004	4.11	1.03	0.00	0.00	0.21	0.06	0.00	0.00
	Sep 2004	2.38	0.32	0.00	0.00	0.33	0.09	0.00	0.00
	Oct 2004	3.92	0.29	0.10	0.03	1.00	0.27	0.00	0.00
	Nov 2004	11.13	1.01	0.00	0.00	0.44	0.12	0.00	0.00
	Dec 2004	5.28	0.18	0.07	0.01	0.79	0.22	0.00	0.00
	Jan 2005	8.14	0.63	0.00	0.00	0.26	0.07	0.00	0.00
	Feb 2005	7.97	0.66	0.00	0.00	1.00	0.27	0.00	0.00
	Mar 2005	3.41	0.13	0.00	0.00	0.00	0.00	0.00	0.00
Murinduko	Apr 2004	0.43	0.03	0.00	0.00	0.22	0.00	0.00	0.00
	May 2004	0.42	0.08	0.00	0.00	1.61	1.61	0.00	0.00
	Jun 2004	0.35	0.14	0.00	0.00	0.98	0.75	0.00	0.00
	Jul 2004	0.91	0.00	0.00	0.00	0.43	0.00	0.00	0.00
	Aug 2004	0.35	0.28	0.00	0.00	0.23	0.00	0.00	0.00
	Sep 2004	1.81	0.88	0.00	0.00	0.32	0.00	0.00	0.00
	Oct 2004	0.49	0.00	0.00	0.00	0.45	0.00	0.00	0.00
	Nov 2004	0.33	0.21	0.00	0.00	0.88	0.38	0.00	0.00
	Dec 2004	1.48	1.48	0.08	0.11	0.63	0.63	0.00	0.00
	Jan 2005	1.34	1.07	0.00	0.00	1.06	0.88	0.08	0.07
	Feb 2005	0.80	0.64	0.00	0.00	0.52	0.17	0.33	0.06
	Mar 2005	1.23	0.45	0.04	0.02	0.48	0.00	0.00	0.00

* Density = mosquitoes per person per night; HBR = human biting rate; SP = sporozoite index; EIR = entomologic inoculation rate; Mbuinjeru = planned rice; Kiamachiri = unplanned rice; Murinduko = non-irrigated.

rice cultivation in planned rice agro-ecosystem was four-fold higher than in the unplanned rice agro-ecosystem. Many studies across the African continent have reported higher densities of *An. gambiae s.l.* in rice-cultivating areas than in neighboring non-irrigated areas.[11,14,15,28,29] In contrast, except for the Ahero rice scheme, Kenya,[12] and rice-growing areas of Madagascar,[30] *An. funestus* is a rare species in irrigated rice agro-ecosystems of Africa. The reason for this is still unknown but could be the result of loss of larval habitats after transformation of natural habitats into rice fields.

It was apparent that in rice irrigated villages, only a small proportion of mosquitoes that entered the house actually fed on humans. Anthropophily for both species was lowest in the planned rice village, moderate in the unplanned rice village, and highest in the non-irrigated village. These findings suggest that the extent of rice cultivation has a significant impact on the blood-feeding behavior of malaria vectors. These findings are consistent with those of previous reports that rice cultivation decreases the degree of human-vector contact by diverting mosquitoes to other hosts.[11,12,14] It has been suggested that rice cultivation empowers the surrounding communities economically, enabling them to protect themselves against mosquito bites.[31] However, a recent study showed that the three villages had similar levels of poverty and social

problems and that income could not explain the observed differences in the degree of anthropophily.[14] Nonetheless, because of the greater number of mosquitoes entering the house in irrigated areas, the resulting nuisance was intolerable and many people recognized the need to sleep under bed nets compared with the low-density non-irrigated areas.[14] High bed net use and large numbers of cattle in irrigated areas are likely to cause a shift from human to cattle feeding by mosquitoes. These findings are consistent with the previous idea that zooprophylaxis may be a potential malaria control strategy in the area.[14] It has also been suggested that anthropophily in *An. gambiae s.s.* increases with age[29] but in contrast, there are reports that cattle feeding increases the parity rate for this species.[32] Neither of the two opposing factors was evaluated for *An. arabiensis* in the present study. Further studies are necessary to assess how various components of disease transmission influence the blood-feeding behavior of malaria vectors in similar areas.

There was no significant difference in the risk of malaria transmission by *An. arabiensis* among the three villages despite the greater variation in mosquito densities and biting rates. These results indicate that rice cultivation in Mwea has no effect on malaria transmission by this species. Many studies in rice irrigated areas of Africa have shown that malaria

transmission can be higher,[7,33] similar,[9] or less[11,12] than in neighboring non-irrigated areas. Because different areas may differ in many aspects even before introduction of water development projects, whether an irrigation project will alter malaria transmission dynamics depends on the local epidemiologic context, particularly the entomologic parameters.[28,34] Our results suggest that the HBI and low vector density were among the factors partly accounting for the lack of a significant difference in the indices of malaria transmission among the three villages. The low HBI had a significant influence in irrigated villages whereas the low vector densities were a limiting factor in the non-irrigated village. Other factors that could have accounted for this observation but were not evaluated in this study include differences in daily survivorship and vectorial capacity.[31,35] A recent study by Diuk-Wasser and others[36] demonstrated a positive relationship between adult survival and vectorial capacity at low mosquito densities and a negative relationship between the two variables at higher mosquito densities. Further studies in the same region showed that adult survivorship was significantly higher in the non-irrigated than in irrigated areas.[37] It is therefore likely that most mosquitoes that emerged from the high-density irrigated areas were short-lived and less efficient at transmitting malaria compared with those in the non-irrigated area.

In contrast with *An. arabiensis*, the risk of malaria transmission by *An. funestus* was significantly higher in the non-irrigated village than in the irrigated villages. This indicates that rice cultivation in the study area reduces the risk of malaria transmission by *An. funestus*. In a study to evaluate the impact of rice cultivation on malaria prevalence in the three study sites, the prevalence of malaria parasites among children ≤ 9 years of age was 0% (n = 21), 17% (n = 53), and 54% (n = 63), in Mbuinjeru, Kiamachiri, and Murinduko, respectively.[14] In our study, infective mosquitoes were observed in all three study sites, an indication that both *An. arabiensis* and *An. funestus* play a significant role in malaria transmission in the area. Mutero and others[14] collected their blood samples between December 2001 and February 2002, which were approximately the same months we observed detectable levels of transmission. Our findings indicate that despite its low density relative to *An. arabiensis*, *An. funestus* does play a significant role in malaria transmission, especially in the non-irrigated areas, because of its high degree of anthropophily, making it worthy of attention to malaria control programs in this area. We did not determine which of the nine known members of the *An. funestus*[22] complex were present in the study area. However, based on our HBI results and the findings of previous studies in the same area,[38] it is likely that *An. parensis* was the dominant species of *An. funestus s.l.* within the rice scheme as opposed to *An. funestus s.s.* in the non-irrigated village.

The low anthophophily of *An. arabiensis*, especially in irrigated areas, may account for the low rates of malaria transmission within the rice scheme despite its higher densities. This information warrants the need to explore the possibility of using zooprophylaxis as a malaria control tactic for similar areas. Zooprophylaxis controls vector-borne diseases by attracting vectors to domestic animals that can act as dead-end hosts.[39] This technique can be an effective strategy for controlling malaria.[40] However, domestic animals may also increase mosquito density, thereby enhancing rather than reducing malaria transmission.[41] In other diseases such as Rift valley fever and Japanese encephalitis, introduction of animals may facilitate amplification and transmission of infection.[42] These findings highlight the need to understand the role of domestic animals in disease transmission in similar areas before adopting zooprophylaxis as a mosquito-borne disease control strategy.

In conclusion, *An. arabiensis* and *An. funestus* were the two prominent vectors of malaria in the study sites. Our study suggests that in Mwea, there is no difference in malaria transmission by *An. arabiensis* between irrigated and non-irrigated areas but in contrast, there is less malaria transmission by *An. funestus* in irrigated than in non-irrigated areas. Among the reasons accounting for this observation was increased zoophily of mosquitoes in irrigated areas and low vector densities in the non-irrigated area. Our findings support the idea that well-studied zooprophylaxis could be an efficient tactic to aid in management of malaria and other mosquito-borne diseases in similar areas.

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REFERENCES

1. Yohannes M, Haile M, Ghebreyesus T, Witten K, Getachew A, Byass P, Lindsay SW, 2005. Can source reduction of mosquito larval habitat reduce malaria transmission in Tigray, Ethiopia? *Trop Med Int Health 10:* 1274–1285.
2. Oomen J, de Wolf J, Jobin W, 1990. *Health and Irrigation. Incorporation of Disease-Control Measures in Irrigation, a Multi-Faceted Task in Design, Construction, Operation.* Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement.
3. Lacey L, Lacey C, 1990. The medical importance of riceland mosquitoes and their control using alternatives to chemical insecticides. *J Am Mosq Contr Assoc 6:* 3–93.
4. International Irrigation Management Institute, 1986. *Proceedings of the Workshop on Irrigation and Vector-Borne Disease Transmission.* Colombo, Sri Lanka: International Irrigation Management Institute.
5. Oomen J, de Wolf J, Jobin W, 1988. *Health and Irrigation: Incorporation of Disease-Control Measures in Irrigation, a Multi-Faceted Task in Design, Construction, Operation.* Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement.
6. Robert V, Van den Broek A, Stevens P, Slootweg R, Petrarca V,

Coluzzi M, Le Goff G, Di Deco MA, Carnevale P, 1992. Mosquitoes and malaria transmission in irrigated rice-fields in the Benoue valley of northern Cameroon. *Acta Trop 52:* 201–204.

7. Coosemans M, 1985. Comparison of malarial endemicity in a rice-growing zone and in a cotton-growing zone in the Rusizi Plain, Burundi. *Ann Soc Belg Med Trop 65:* 187–200.

8. Sissoko MS, Dicko A, Briet OJT, Sissoko MS, Sagara I, Keita H, Sogoba M, Rogier C, Toure Y, Doumbo O, 2004. Malaria incidence in relation to rice cultivation in the irrigated Sahel of Mali. *Acta Trop 89:* 161–170.

9. Robert V, Gazin P, Boudin C, 1985. The transmission of malaria in a wooded savanna zone and a rice-growing zone in the vicinity of Bobo Dioulasso (Burkina Faso). *Ann Soc Belg Med Trop 65:* 201–214.

10. Ijumba JN, 1997. *The Impact of Rice and Sugarcane Irrigation on Malaria Transmission in the Lower Moshi Area of Northern Tanzania.* Copenhagen, Denmark: Department of Population Biology, Zoological Institute of Denmark, University of Copenhagen.

11. Ijumba J, Mosha F, Lindsay S, 2002. Malaria transmission risk variations derived from different agricultural practices in an irrigated area of northern Tanzania. *Med Vet Entomol 16:* 28–38.

12. Githeko A, Service MW, Mbogo CM, Atieli FK, Juma FO, 1993. *Plasmodium falciparum* sporozoite and entomological inoculation rates at the Ahero rice irrigation scheme and the Miwani sugar-belt in western Kenya. *Ann Trop Med Parasitol 87:* 379–391.

13. Faye O, Fontenille D, Gaye O, 1995. Malaria and rice growing in the Senegal River delta (Senegal). *Ann Soc Belg Med Trop 75:* 179–189.

14. Mutero C, Kabutha C, Kimani V, Kabuage L, Gitau G, Ssennyonga J, Githure J, Muthami L, Kaida A, Musyoka L, Kiarie E, Oganda M, 2004. A transdisciplinary perspective on the links between malaria and agroecosystems in Kenya. *Acta Trop 89:* 171–186.

15. Muturi J, Shililu J, Jacob B, Githure J, Gu W, Novak R, 2006. Mosquito species diversity and abundance in relation to land use in a riceland agroecosystem in Mwea, Kenya. *J Vector Ecol 31:* 129–137.

16. Muturi E, Shililu J, Gu W, Jacob B, Githure J, Novak R, 2007. Larval habitat dynamics and diversity of *Culex* mosquitoes in rice agro-ecosystem in Mwea, Kenya. *Am J Trop Med Hyg 76:* 95–102.

17. Ijumba J, Mwangi R, Beier JC, 1990. Malaria transmission potential of *Anopheles* mosquitoes in the Mwea-Tebere irrigation scheme, Kenya. *Med Vet Entomol 4:* 425–432.

18. Mutero CM, Blank H, Konradsen F, Hoek W, 2000. Water management for controling the breeding of *Anopheles* mosquitoes in rice irrigation schemes in Kenya. ICIPE, Nairobi. *Acta Trop 76:* 253–256.

19. Muturi EJ, Mwangangi JM, Shililu J, Muriu S, Jacob B, Kabiru EW, Gu W, Mbogo C, Githure J, Novak R, 2007. Mosquito species succession and the physicochemical factors affecting their abundance in rice fields in Mwea, Kenya. *J Med Entomol 44:* 336–344.

20. World Health Organization, 1975. *Manual on Practical Entomology in Malaria. Part II. Methods and Techniques.* Geneva: World Health Organization.

21. Edwards F, 1941. *Mosquitoes of the Ethiopian Region. III. Culicine Adults and Pupae.* London: British Museum of Natural History.

22. Gillies MT, Coetzee M, 1987. *A Supplement to the Anophelinae of Africa South of the Sahara (Afro-Tropical Region).* Johannesberg, South Africa: *Publication of the South African Institute of Medical Research 55:* 1–143.

23. Beier JC, Perkins PV, Wirtz RA, Koros J, Diggs D, Gargan TP, Koech DK, 1988. Blood meal identification by direct enzyme-linked immunosorbent assay (ELISA), tested on *Anopheles* (Diptera: Culicidae) in Kenya. *J Med Entomol 25:* 9–16.

24. Wirtz R, Zavala F, Graves P, Andre G, 1987. Field evaluation of ELISA for *Plasmodium falciparum* and *Plasmodium vivax* sporozoites in mosquitoes (Diptera: Culicidae) from Papua New Guinea. *J Med Entomol 24:* 433–437.

25. Charlwood JD, Smith T, Kihonda J, Heiz B, Billingsley PF, Takken W, 1995. Density independent feeding success of malaria vectors (Diptera: Culicidae) in Tanzania. *Bull Entomol Res 85:* 29–35.

26. Beier JC, 2002. Vector incrimination and entomological inoculation rates. *Methods Mol Med 72:* 3–11.

27. Githeko A, Service M, Mbogo C, Atieli F, 1996. Resting behaviour, ecology and genetics of malaria vectors in large scale agricultural areas of Western Kenya. *Parassitologia 38:* 481–489.

28. Briet J, Dossou-Yovo J, Akodo E, van de Giesen N, Teucher M, 2003. The relationship between *Anopheles gambiae* density and rice cultivation in the savannah and forest zone of Côte d'Ivoire. *Trop Med Int Health 8:* 439–448.

29. Dolo G, Briet OJ, Dao A, Traore SF, Bouare M, Sogoba N, Niare O, Bagayogo M, Sangare D, Teuscher T, Toure YT, 2004. Malaria transmission in relation to rice cultivation in the irrigated Sahel of Mali. *Acta Trop 89:* 147–159.

30. Marrama L, Rajaonarivelo E, Laventure S, Rabarison P, 1995. *Anopheles funestus* and rice culture on the Plateau of Madagascar. *Cahiers Etudes Recherches Francophones Sante 5:* 415–419.

31. Ijumba J, Lindsay S, 2001. Impact of irrigation on malaria in Africa: paddies paradox. *Med Vet Entomol 15:* 1–11.

32. Robert V, Petrarca V, Coluzzi M, Etudin C, Carnevale P, Chippaux JP, Diomande L, 1991. Etude des taux de parturite et d'infection du complexe *Anopheles gambiae* dans la riziere de la Vallee du Kou, Burkina Faso. Robert V, Chippaux JP, Diomande L, eds. *Le Paludisme en Afrique de l'Ouest: Etudes Entomologiques et Epidemiologiques en Zone Rizicole et en Milieu Urbain.* Paris: Office de la Recherche Scientifique et Technique d'Outre-Mer, 17–35.

33. Marrama L, Jambou R, Rakotoarivony I, 2004. Malaria transmission in southern Madagascar: influence of the environment and hydro-agricultural works in sub-arid and humid regions. Part 1. *Acta Trop 89:* 193–203.

34. Keiser J, Caldas de Castro M, Maltese MF, Bos R, Tanner M, Singer BH, Utzinger J, 2004. The effect of irrigation and large dams on the burden of malaria on global and regional scale. *Am J Trop Med Hyg 72:* 392–406.

35. Garret-Jones C, Shidrawi GR, 1969. Malaria vectorial capacity of a population of *Anopheles gambiae. Bull World Health Organ 40:* 531–545.

36. Diuk-Wasser MA, Toure MB, Dolo G, Bagayogo M, Sogoba N, Traore SF, Manoukis N, Taylor CE, 2005. Vector abundance and malaria transmission in rice-growing villages in Mali. *Am J Trop Med Hyg 72:* 725–731.

37. Manoukis N, Toure MB, Sissoko I, Doumbia S, Traore SF, Diuk-Wasser MA, Taylor CE, 2006. Is vector body size the key to reduced malaria transmission in the irrigated region of Niono, Mali? *J Med Entomol 43:* 820–827.

38. Kamau L, Koekemoer LL, Hunt RH, Coetzee M, 2003. *Anopheles parensis:* the main member of the *Anopheles funestus* (Diptera: Culicidae) species group found resting inside human dwellings in Mwea area of central Kenya. *J Am Mosq Control Assoc 19:* 130–133.

39. Seyoum A, Balcha F, Balkew M, Ali A, Gebre-Michael T, 2002. Impact of cattle keeping on human biting rate of anopheline mosquitoes and malaria transmission around Ziway, Ethiopia. *East Afr Med J 79:* 485–490.

40. Sota T, Mogi M, 1989. Effectiveness of zooprophylaxis in malaria control: a theoretical inquiry, with a model for mosquito populations with two bloodmeal hosts. *Med Vet Entomol 3:* 337–345.

41. Bouma M, Rowland M, 1995. Failure of passive zooprophylaxis: cattle ownership in Pakistan is associated with a higher prevalence of malaria. *Trans R Soc Trop Med Hyg 89:* 351–353.

42. Arunachalam N, Samuel P, Hiriyan J, Rajendran R, Dash A, 2005. Short report: observations on the multiple feeding behavior of *Culex tritaeniorhynchus* (Diptera: Culicidae), the vector of Japanese encephalitis in Kerala in Southern India. *Am J Trop Med Hyg 72:* 198–200.