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MAJOR ARTICLE

Irrigation-Induced Environmental Changes Sustain Malaria Transmission and Compromise Intervention Effectiveness

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Background. Irrigated agriculture enhances food security, but it potentially promotes mosquito-borne disease transmission and affects vector intervention effectiveness. This study was conducted in the irrigated and nonirrigated areas of rural Homa Bay and Kisumu Counties, Kenya.

Methods. We performed cross-sectional and longitudinal surveys to determine *Plasmodium* infection prevalence, clinical malaria incidence, molecular force of infection (*mol*FOI), and multiplicity of infection. We examined the impact of irrigation on the effectiveness of the new interventions.

Results. We found that irrigation was associated with >2-fold higher *Plasmodium* infection prevalence and 3-fold higher clinical malaria incidence compared to the nonirrigated area. Residents in the irrigated area experienced persistent, low-density parasite infections and higher *mol*FOI. Addition of indoor residual spraying was effective in reducing malaria burden, but the reduction was more pronounced in the nonirrigated area than in the irrigated area.

Conclusions. Our findings collectively suggest that irrigation may sustain and enhance *Plasmodium* transmission and affects intervention effectiveness.

Keywords. indoor residual spraying; irrigation; malaria; molecular force of infection; *Plasmodium* infection prevalence.

Despite substantial gains in malaria control since the early 21st century, facilitated by mass distribution of insecticide-treated nets, indoor residual spraying (IRS), and artemisinin-based combination therapies, global progress in reducing the malaria burden has stagnated [1]. Malaria remains endemic in 87 countries worldwide, with >90% of malaria cases and deaths occurring in Africa [1]. At the same time, millions of people in sub-Saharan Africa are affected by food insecurity, largely due to overreliance on traditional rain-fed agriculture [2–4]. To promote food security and alleviate poverty, numerous dams, microdams, and irrigation schemes have been developed in Africa in the past 2 decades [5–7]. Although irrigated agricultural development has clear socioeconomic benefits [3, 8, 9], environmental modifications resulting from such developments may promote the transmission of vector-borne diseases [10–14]. Flood irrigation, in particular, creates additional potential breeding habitats for malaria vectors [15–17]. Understanding the relationships between irrigated agriculture and malaria transmission dynamics in the context of intensified antimalarial interventions is vital to mitigating potential ramifications of future agricultural development projects on malaria control.

In previous studies, researchers have found associations between agricultural irrigation development and increased indoor-resting mosquito density and entomological inoculation rate [18–20]. However, changes in malaria vector populations do not necessarily translate into increased malaria risk. A recent cross-sectional study in Western Kenya reported significantly higher malaria parasite prevalence in an irrigated area compared to the adjacent nonirrigated area during the dry season, implying that irrigation may help to sustain the malaria transmission [21]. However, crucial evidence from longitudinal and clinical malaria data are lacking [8, 12, 17, 22].

Few studies have examined the impact of irrigation on the effectiveness of malaria vector interventions [17]. The mass distribution of free long-lasting insecticidal nets (LLINs) in 2006 in malaria-endemic African countries marked the scale-up

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era of malaria interventions [23, 24]. Due to widespread vector resistance to pyrethroid insecticides [25], new, enhanced interventions using insecticides with different modes of actions such as IRS with the organophosphate-based Actellic and piperonyl butoxide-treated LLINs have more recently been implemented in African countries [26–28]. Few studies have addressed how scaled-up and newer malaria interventions may mitigate the risks posed by irrigated agriculture [26–28].

In this study, we investigate how irrigation affects malaria ecology and IRS effectiveness in Western Kenya using a combination of field epidemiological and laboratory molecular investigations. The findings of this study will be important for guiding the implementation of enhanced malaria interventions to mitigate risks associated with irrigation.

METHODS

Study Area

This study was conducted in the Lake Victoria shore area of Western Kenya (Supplementary Figure 1), which reports a bimodal rainy season: a long rainy season from late March to June and a short rainy season from October to November [29]. Malaria transmission in the region is perennial and peaks during the long rainy season [30, 31].

We selected clusters of households in Homa Bay County ($n = 20$) and Kisumu County ($n = 9$). Ten clusters each were randomly selected from the irrigated and nonirrigated areas of Homa Bay (Supplementary Figure 1). A cluster is defined as a village or group of villages covering an area of approximately 2 km^2 and a population of 600–1000 residents. Clusters are separated by a buffer zone of approximately 1 km. Nonirrigated clusters were selected at >3-km distance from irrigation schemes. Homa Bay County has received ongoing IRS interventions using Actellic 300CS insecticides once per year in February since 2018 with >95% coverage [27, 32]. We additionally selected clusters of households in Kisumu County, with neither IRS intervention nor irrigation (Supplementary Figure 1*A*), as a comparison group. Kisumu site practices traditional rain-fed agriculture (ie, no irrigation), with maize as a staple crop along with scatter of bananas and vegetables (Supplementary Figure 1*A*). Major malaria vectors in both areas are *Anopheles gambiae* sensu lato and *Anopheles funestus* sensu lato [27, 30, 32, 33].

Epidemiological Investigations

Longitudinal Household Visits, Active Case Surveillance of Clinical Incidence. To evaluate the impact of irrigation on clinical malaria incidence, active case surveillance (ACS) was conducted on a prospective cohort across all 20 clusters in Homa Bay (Supplementary Figure 2) [34]. All residents who were willing to participate and who provided signed consent and/or assent (for minors under the age of 18) were included in the study. Participants were visited biweekly and screened for clinical malaria [34]. The age and sex of each participant were recorded during the first visit. A clinical malaria case was defined as an individual with uncomplicated malaria-related symptoms (fever with axillary temperature ≥37.5°C or subjective fever within the previous 2 days, chills, malaise, headache, myalgia) at the time of examination and laboratory confirmed *Plasmodium*-positive by rapid diagnostic test (RDT) [34]. Rapid diagnostic tests were administered on site for participants who exhibited malaria symptoms, and RDT-positive cases were referred to the nearest health facility for free treatment according to governmental guidelines [35]. The ACS cohort was followed from October 2019 to November 2021. Malaria incidence rate was calculated as cases/1000 person-years based on RDT results.

Cross-Sectional Seasonal Asymptomatic* Plasmodium *Infection Prevalence. To measure the *Plasmodium* infection in different irrigation areas and seasonal changes, parasite infection surveys were conducted in Homa Bay (20 clusters) in February, June, and/or November from 2017 to 2020 (Supplementary Figure 2). During each survey, 80–100 participants were randomly selected from each cluster. Finger-prick blood sampling was conducted to prepare filter paper dried blood spots (DBS) and thin and thick blood smears [30]. Blood smears were examined using microscopy, and DBS were screened for parasite infections using 18-second quantitative polymerase chain reaction (qPCR) [21]. Parasite prevalence was calculated as the number of positive samples divided by the total samples examined.

Longitudinal Cohort,* Plasmodium *Infection, and Molecular Study. To examine the effects of irrigation on temporal patterns of infection, molecular force of infection (*mol*FOI) and infection complexity, we conducted monthly finger-prick blood sampling and collected filter paper DBS from approximately 700 randomly selected participants from the ACS cohort (Supplementary Figure 2). Parasite infection was assessed by 18-second qPCR for *Plasmodium malariae* and *Plasmodium ovale* and *var*ATS qPCR for *Plasmodium falciparum* [21]. A new infection episode was defined as a positive qPCR result detected at least 28 days after a previous infection [36].

To study malaria infections at the clone level, amplicon deep sequencing of the *P falciparum cpmp* gene was used to identify and differentiate parasite clones based on existing protocols [33, 37]. The limit of detection for minority clones was set at 2%. Median and mean infection complexities were determined at the individual-level and compared between irrigation and nonirrigation zones using Wilcoxon rank-sum tests with a Bonferroni correction [38]. The *mol*FOI was calculated as the number of newly acquired clones per individual per year. Difference in *mol*FOI between study areas was compared using a generalized estimating equation model assuming AR1 autocorrelation.

Impact of Irrigation on Malaria Ecology and Interventions

To examine how irrigation affects the effectiveness of new IRS interventions, indoor-resting mosquito populations were monitored monthly from November 2017 to December 2021 in 4 randomly selected clusters each from the irrigated and nonirrigated areas in Homa Bay and in 3 clusters in Kisumu. Each month, 10 houses were randomly selected per cluster and mosquitoes were collected using the pyrethrum spraying catch method [30].

Longitudinal monthly parasitological surveys were conducted from November 2017 to December 2021 to determine *Plasmodium* infection dynamics in school-aged children (Supplementary Figure 2), the group with the highest infection prevalence [34]. Each month, school children aged 6–13 from 3 to 4 clusters were randomly selected (80–120 children/cluster) from both the irrigated and nonirrigated areas in Homa Bay as well as from Kisumu. Finger-prick blood samplings were conducted for the preparation of thin and thick blood smears [30]. Blood smears were examined using microscopy, and monthly infection prevalence was calculated as described earlier [30].

Data Statistical Analysis

A χ^2 test was used for the comparisons of incidence and parasite prevalence between irrigated and nonirrigated areas or between age and sex groups. To analyze longitudinal surveillance data, we used Poisson regression (cluster-based) to compare differences in *Plasmodium* infection prevalence between study sites. AR1 autocorrelation was assumed. Regarding the biweekly ACS data, we compared uncomplicated malaria incidence rates between irrigated and nonirrigated areas using Poisson regression, assuming an AR1 autocorrelation.

The potential impact of irrigation on the effectiveness of IRS was analyzed through risk ratio (RR) assessment. We compared 3 indicators, ie, vector density, *Plasmodium* infection prevalence, and uncomplicated clinical malaria incidence, before and after IRS and used the Kisumu site as a non-IRS control (Supplemental File 1). The correlation between IRS and observed transmission dynamics was analyzed using the generalized additive model (Supplemental File 1). All data analyses were completed using R 4.0.3 (The R Foundation for Statistical Computing, Vienna, Austria).

Scientific and Ethical Clearance

Ethical clearance was obtained from the Ethical Review Committee of Maseno University, Kenya (MSU/DRPI/MUERC/00778/19) and the Institutional Review Board of the University of California, Irvine, Calfornia (HS# 2017-3512). Volunteers were enrolled from primary schools in the study sites through school administrators with the permission of the division office of the Ministry of Health. Written assent for children (<18 years of age) was obtained by the participants and their parents or guardians. For parasitological surveillance, written consent and assent for households was obtained from the head of the household and each individual who was willing to participate in the study. Inclusion criteria included providing informed consent and having no reported chronic or acute illness except malaria. Individuals who were unwilling to participate and infants under the age of 6 months were excluded from the study. According to the standard malaria treatment guidelines of the Ministry of Health of Kenya, asymptomatic infections were not treated with antimalarials, whereas symptomatic volunteers were referred to the local government hospital or clinic for diagnosis and treatment free of charge. For entomological surveillance, oral consent was obtained from the head of the household for each participating household. In all surveillance activities, personal identifiers were not included in the data.

RESULTS

Plasmodium Infection Prevalence: Irrigation Verus Nonirrigation

In Homa Bay, infection prevalence decreased substantially in both the irrigated and nonirrigated areas (Figure 1). The RR, ie, the ratio of *Plasmodium* infection prevalence detected by PCR in the irrigated area over that in the nonirrigated area, increased slightly from 1.53 (95% CI, 1.31–1.80) in 2018 to 1.78 (95% confidence interval [CI], 1.30–2.44) in 2021 (χ^2 test $P < .0001$ for all), indicating a slightly greater reduction in prevalence in the nonirrigated area between 2018 and 2021.

Age and sex distribution of infections showed different patterns between irrigated and nonirrigated areas in Homa Bay (χ^2 test, $P < .05$) (Supplementary Figure 3). Parasite species were more diverse in the irrigated area of Homa Bay (ie, higher proportion of mixed infections; χ^2 test, $P < .05$) (Supplementary Figure 4).

Uncomplicated *Plasmodium* Clinical Incidence: Irrigated Versus Nonirrigated

Over the 23-month ACS period in Homa Bay, we made 220 230 person-visits to homes. We detected 8480 fever cases and 984 RDT-confirmed malaria cases (Table 1). The clinical incidence rate was 3-fold higher in the irrigated area compared to the nonirrigated area (odds ratio [OR] = 2.66; 95% CI, 2.33–3.02; $\chi^2 = 239.76$; d.f. = 1; $P < .0001$) (Table 1).

Clinical incidence was consistently higher in irrigated areas compared to nonirrigated areas (Poisson regression, Rao statistic = 3240.7, d.f. = 1, $P < .0001$) (Figure 2*A*). The decline in clinical incidence was more pronounced in nonirrigated areas compared to irrigated areas (incidence rate ratio: 2.39 in 2020 and 3.00 in 2021). Clusters with high incidence (>100 cases/year per 1000 population-at-risk) were concentrated in the irrigated area, whereas most clusters (8 of 10) in the nonirrigated area had an incidence of <100 cases/year per 1000 population-at-risk (Figure 2*B*).

Parasite Infection Dynamics, Molecular Force of Infection, and Multiplicity of Infection

From the cohort study, a total of 11 157 blood samples were analyzed by qPCR. The overall parasite infection rate was 6.6% (400 of 6037) in the irrigated area compared to 2.3% (119 of 5120) in the nonirrigated area (OR = 3.0; 95% CI, 2.4–3.6; $\chi^2 = 115.58$; d.f. = 1; $P < .0001$) (Supplementary Figure 5*A*).

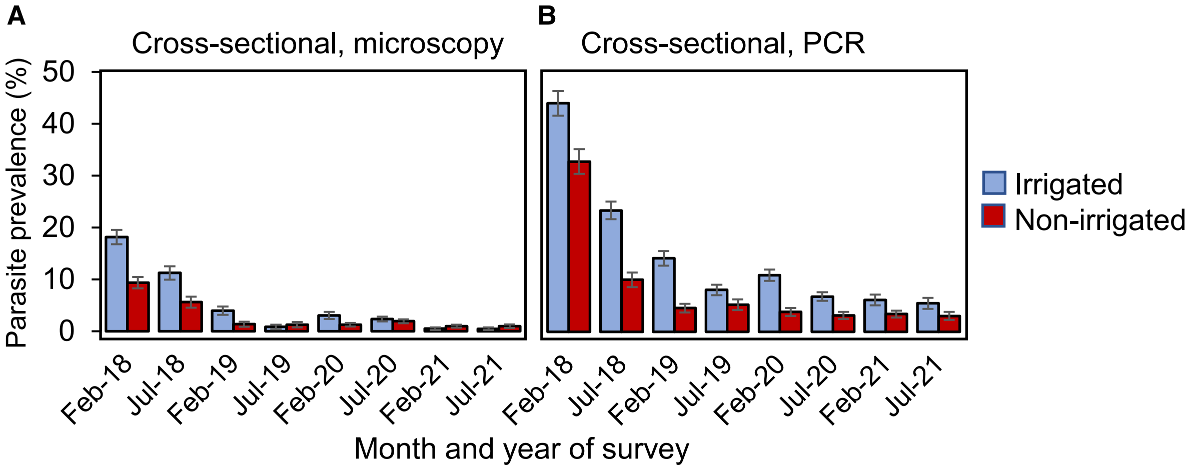

Figure 1. (*A* and *B*) Seasonal changes in *Plasmodium* infection prevalence in different irrigation areas in Homa Bay (10 clusters each in irrigated and nonirrigated areas) detected by microscopy (*A*) and 18S rDNA polymerase chain reaction (PCR) (*B*).

Table 1. Summary of Active Case Surveillance in Homa Bay, January 2020 to November 2021

Items	Irrigated	Nonirrigated
N clusters	10	10
Population enrolled	1828	3066
Visits (person-times)	82 264	137 966
Fever cases	4406	4074
RDT positive cases	602	382
Incidence rate (95% CI) (cases/1000 people/year)[a]	148.9 (132.5–165.2)	56.3 (48.2–64.5)

Abbreviations: CI, confidence interval; RDT, rapid diagnostic test.

[a] Uncomplicated malaria incidence rate was calculated as an average over the 10 clusters, and time-at-risk was based on actual visits.

To calculate the *mol*FOI, a total of 330 samples were sequenced, resulting in 221 unique clones. The *mol*FOI was approximately 7.5-fold higher in the irrigated group than the nonirrigated group (0.643 vs 0.085 clones/individual per year) (Wald statistics = 32.50, d.f. = 1, $P < .0001$) (Supplementary Figure 5*B*).

Temporal patterns of infections showed that individuals in the irrigated area more commonly experienced a higher number of consecutive months with malaria infections compared to individuals in the nonirrigated area (Supplementary Figure 5*C*). The MOI was persistently higher in the irrigated area compared to the nonirrigated area, but the difference was statistically insignificant (Supplementary Figure 6). Mean parasitemia was significantly lower in the irrigated area than in the nonirrigated area ($F_{1,402} = 6.77$, $P = .0096$) (Supplementary Figure 7).

Trend Analysis and Potential Indoor Residual Spraying Impact

Monthly Indoor-Resting Anopheles Dynamics

In Homa Bay, indoor-resting *Anopheles* density was consistently higher in the irrigated area than in the nonirrigated area (analysis of variance with repeated measures, $F_{1,88} = 102.64$; $P < .0001$) (Figure 3*A*). *Anopheles* density showed a clear peak each year approximately May–July in Kisumu; the same trend was not observed in Homa Bay (Figure 3*A*). Overall, *Anopheles* density declined significantly in both the irrigated area ($F_{2,30} = 4.47$, $P = .020$) and the nonirrigated area of Homa Bay ($F_{2,30} = 3.91$, $P = .031$) from 2018 to 2021, but the decline was more pronounced in the nonirrigated area. In Kisumu, *Anopheles* density increased significantly from 2018 to 2021 ($F_{2,30} = 16.86$, $P < .0001$).

Dynamics of Infection Prevalence in School-Aged Children

Infection prevalence was stable and high in Kisumu, with a peak season approximately May every year (Figure 3*B*). In Homa Bay, infection prevalence in the irrigated area was similar to that in Kisumu in January 2018, but prevalence began declining substantially in Homa Bay during the study period (Figure 3*B*). The absolute difference in infection prevalence between the irrigated and nonirrigated areas in Homa Bay diminished over the follow-up period; however, the difference between the 2 zones remained significant (Poisson regression Wald statistics 7.54, $P = .0060$) (Figure 3*B*).

Potential Indoor Residual Spraying Impact

At the beginning of this study from November 2017 to February 2018 (before IRS), *Plasmodium* infection prevalence was 2-fold higher in the irrigated than in the nonirrigated area in Homa Bay (20.7% vs 10.2%; OR = 2.29; 95% CI, 1.76–2.99; $\chi^2 = 39.51$; d.f. = 1; $P < .0001$) (Figure 3), indicating that the effectiveness of routine LLIN interventions (before IRS) was potentially compromised by irrigation.

Direct comparison between 3 months pre-IRS (December to February) and 9 months post-IRS (March to November) revealed increases in infection prevalence and vector abundance

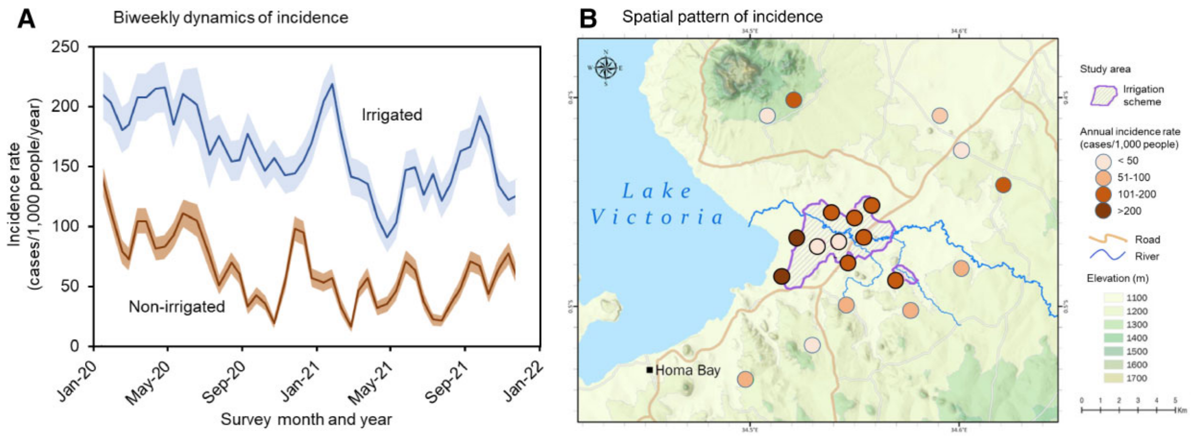

Figure 2. Active case surveillance in Homa Bay: (*A*) biweekly dynamics of clinical malaria incidence (cases/1000 people/month) in the irrigated and nonirrigated areas, with shaded areas representing 95% confidence intervals; and (*B*) distribution of average clinical incidence in each study cluster. Each dot represents 1 cluster.

during post-IRS months in Kisumu (no IRS throughout) but not in Homa Bay, where IRS was implemented (Supplement File 1).

Dynamics of uncomplicated *Plasmodium* clinical incidence, infection prevalence, and vector density were significantly negatively correlated with the number of rounds of IRS in the Homa Bay area but not in Kisumu (Table 2, Supplement File 1). Relatively higher reduction (ie, lower adjusted RR) in uncomplicated clinical malaria incidence, *Plasmodium* infection prevalence, and vector density were observed in the nonirrigated clusters compared to the irrigated clusters in Homa Bay (Table 2, Supplemental File 1).

DISCUSSION

New and enhanced vector control measures are being rolled out across Africa to complement core vector control interventions and to reinvigorate progress towards malaria elimination [39]. Simultaneously, African governments are expected to increase investment in agricultural development (eg, irrigation schemes) to combat food insecurity and to accommodate rapid population growth. Although agricultural development confers clear economic benefits to local communities [9, 17, 19], irrigation-induced environmental changes can lead to enhanced malaria transmission that, in turn, may compromise the effectiveness of elimination efforts. In this study, we conducted comprehensive cross-sectional and longitudinal epidemiological and molecular investigations in both irrigated and nonirrigated areas exhibiting perennial malaria transmission. We found higher clinical malaria incidence and greater prevalence of *Plasmodium* infections in irrigated area. Irrigation filled the transmission gaps during the dry season by facilitating persistent and diverse low-parasitemia infections year-round. More importantly, we found that IRS with Actellic insecticide was effective in reducing malaria burden in both irrigated and nonirrigated areas, but the reduction in disease burden was less pronounced in the irrigated area, likely due to persistent residual outdoor transmission [32]. Most of the previous studies have provided direct evidence regarding the impact of irrigation on vector bionomics and infection prevalence [17]. Through longitudinal active surveillance, we demonstrate here that irrigation indeed increased clinical malaria incidence and sustained persistent *Plasmodium* infections. Thus, we conclude that irrigation likely compromised the effectiveness of the enhanced vector intervention in our study area.

Although some previous studies concluded that irrigation increased malaria risk only in areas of unstable transmission [17, 40], other studies did not support this conclusion [19]. We investigated the effects of irrigation on malaria risk in Homa Bay, where malaria transmission is perennial and stable [29]. Over the 4-year study period, all malaria transmission indicators—community parasite prevalence, clinical malaria, and *mol*FOI—were significantly higher in the irrigated area than in the nearby nonirrigated area. Furthermore, communities in the irrigated area suffered persistent asymptomatic malaria infections characterized by lower parasitemia and higher parasite genetic diversity compared to those in the nonirrigated areas. The lower-parasitemia infections in the irrigated communities indicate potentially higher level of herd immunity acquired through more frequent infections [41, 42]. In addition, gene-flow studies have indicated that irrigated areas serve as a reservoir of parasites for nearby nonirrigated areas [21], which may explain the near identical mean/median MOI between the irrigated and the nonirrigated areas, ie, parasites in both areas are from the same source. These findings show that even in areas of stable malaria transmission, the introduction of irrigation can have a great impact on malaria burden, making transmission more stable.

Prospective cohort active case surveillance provided important longitudinal information on the patterns of malaria infections in both irrigated and nonirrigated areas. Clinical malaria

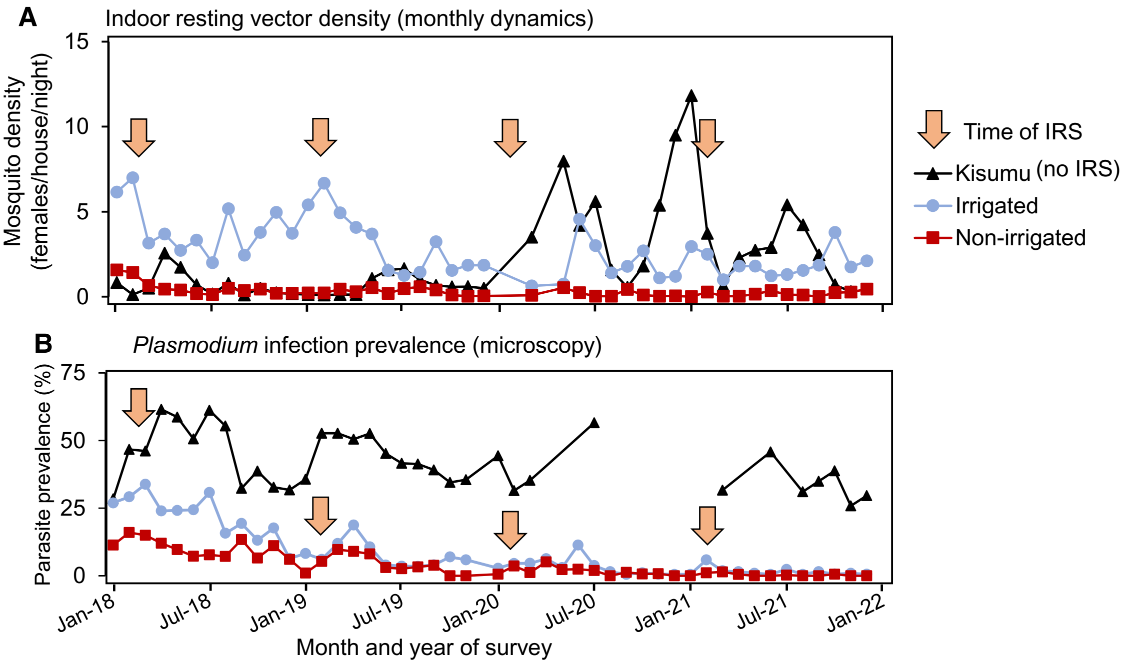

Figure 3. (*A*) Monthly dynamics of indoor-resting malaria vector density in Homa Bay and in Kisumu. (*B*) Monthly changes in *Plasmodium* infection prevalence of school-age children in different irrigation areas of Homa Bay and Kisumu detected by microscopy. Blood sampling was not done in most months from March 2020 to July 2021. Four clusters were selected in each irrigation zone of Homa Bay and 3 clusters in Kisumu for both surveys. The yellow arrows indicate the months when IRS was carried out in Homa Bay; no indoor residual spraying (IRS) was carried out in Kisumu.

Table 2. Modeling of Malaria Transmission Risks Against IRS[a]

Indicator Variable	Kisumu (No IRS)		Irrigated, Homa Bay		Nonirrigated, Homa Bay	
	Risk Ratio (95% CI)	*P*	Risk Ratio (95% CI)	*P*	Risk Ratio (95% CI)	*P*
Malaria Incidence						
Seasonality	1.04 (.92–1.24)	.5228	0.95 (.74–1.23)	.6955	0.56 (.31–1.02)	.0562
IRS [9M-post/3M-pre]	**4.80 (1.45–26.94)**[b]	**.0099**	0.94 (.85–1.05)	.2722	**0.70 (.54–0.90)**	**.0058**
Months since last IRS	1.38 (.86. 2.29)	.1741	0.98 (.97–1.01)	.0681	**0.95 (.91–0.99)**	**.0277**
Rounds of IRS	1.14 (.91–1.45)	.2613	**0.82 (.75–.90)**	**<.0001**	**0.63 (.50–0.78)**	**<.0001**
Infection Prevalence						
Seasonality	**1.72 (1.20–2.49)**	**.0047**	**1.64 (1.06–2.60)**	**.0272**	1.15 (.62–2.13)	.6496
IRS [9M-post/3M-pre]	0.94 (.80–1.10)	.4267	**0.67 (.55–0.81)**	**.0001**	**0.71 (.52–0.96)**	**.0238**
Months since last IRS	0.97 (.94–1.02)	.0997	**0.95 (.91–0.99)**	**.0230**	0.97 (.90–1.03)	.3222
Rounds of IRS	0.91 (.82–1.02)	.0754	**0.37 (.30–0.44)**	**<.0001**	**0.41 (.31–0.51)**	**<.0001**
Mosquito Density						
Seasonality	1.75 (.41–10.07)	.4513	0.82 (.43–1.62)	.5547	0.88 (.34–2.41)	.7970
IRS [9M-post/3M-pre]	**2.25 (142–3.74)**	**.0012**	1.05 (.84–1.33)	.6576	0.89 (.60–1.29)	.5205
Months since last IRS	1.00 (.92–1.09)	.9712	**0.96 (.92–0.99)**	**.0484**	**0.91 (.83–1.29)**	**.0144**
Rounds of IRS	**1.91 (1.45–3.10)**	**<.0001**	**0.76 (.68–0.84)**	**<.0001**	**0.46 (.29–0.61)**	**<.0001**

Abbreviations: CI, confidence interval; IRS, indoor residual spraying.

[a] Risk ratio <1 equivalent to negative β-values. 9M-post/3M-pre: 9 months postintervention (March–November) against 3 months baseline (December to February).

[b] Bold font numbers indicating $P < .05$.

cases reported at health facilities have been used for intervention evaluation [27], but these passively detected cases likely underestimate the true malaria incidence [34], because many people in Western Kenya do not seek treatment at health facilities [24]. With biweekly home visits, active case surveillance should be able to capture most malaria cases. In this study, active case surveillance revealed a 3-fold higher malaria incidence in the irrigated area compared to the nonirrigated area of the Homa Bay study site, providing direct evidence of the impact of irrigation on clinical malaria. Infection incidence was consistently higher in the irrigated area compared to the nonirrigated area. It is interesting to note that we observed a steadily declining pattern in malaria incidence in the Homa Bay site, likely due to continuous, annual IRS implementation since 2018 [26, 43]. More importantly, monthly cohort blood sampling detected repeated (ie, persistent) infections with low parasitemia in the irrigated area but not in the nonirrigated area. These results highlight the importance of longitudinal cohort surveillance, which has not been conducted in previous studies [17, 19, 21, 26, 44], in assessing the impact of irrigation on maintaining malaria transmission.

Despite high LLIN coverage, *Plasmodium* infection prevalence in the study areas was high at the beginning of the study in early 2018. The new IRS intervention was first implemented in 2018, covering Homa Bay County but not Kisumu County [32, 43]. This difference in interventions provided a unique opportunity to evaluate how the interaction of intervention and irrigation affects malaria ecology [26]. Evaluation of the IRS intervention conducted in neighboring Migori County, Western Kenya showed that IRS with Actellic insecticide was effective in reducing vector density and malaria slide positivity rates at health facilities [27]. In the Kisumu study site, where no IRS was implemented, vector density and *Plasmodium* infection prevalence all remained relatively consistent from 2017 to 2021, whereas in the Homa Bay site, *Plasmodium* infection prevalence and malaria incidence in both the irrigated and nonirrigated areas showed steady declining trends starting in 2018, likely caused by the annual IRS intervention [26, 27]. However, declines in clinical malaria incidence were less pronounced in the irrigated area compared to the nonirrigated area, implying that the impact of IRS was probably compromised by irrigation. We should note that although IRS was effective in reducing *An funestus* population density [27], density of *An gambiae* was consistently high in the irrigated area, likely due to the outdoor-resting behavior of *Anopheles arabiensis* in the study area as evidenced in previous studies [32, 45]. Mosquito habitats created by irrigation may help to sustain the outdoor-resting vector population density, even when IRS is effective at reducing indoor-resting and outdoor vector population densities, thereby maintaining malaria transmission in irrigated areas.

The major limitation of this study is the number of irrigated and control sites. Additional irrigated sites and sites with diverse ecological settings should be studied to confirm our findings. However, this study included 29 clusters in the irrigated and nonirrigated areas, and we provided extensive evidence to support our conclusions through large sample sizes of cross-sectional and longitudinal parasite and clinical malaria observations. These large sample size data may help to minimize the effect of diversity of ecological settings. Another limitation is the RDT-based estimation of malaria incidence. The RDT tests have a lower sensitivity in detecting low-parasitemia infections compared with PCR [46, 47]. Thus, malaria incidence was likely underestimated by using RDT results. However, RDT is the fastest method for malaria infection diagnosis and leads to quicker treatment in field settings, hence many malaria-endemic African countries, including Kenya, have adopted the policy of universal diagnosis using RDT in health facilities and communities [35, 43, 48]. Because the same type of RDTs were administrated in all ACS clusters, differential misclassification was unlikely. Indeed, we observed comparable declines in malaria incidence between irrigated and nonirrigated areas.

CONCLUSIONS

In conclusion, the irrigated area supported more and longer-lasting aquatic habitats [45], which likely contributes to stable, perennial malaria transmission. Higher parasite prevalence and malaria incidence were observed in the irrigated area than in the nonirrigated area. The current Actellic IRS intervention was less effective at reducing clinical malaria in the irrigated area compared to the nonirrigated area. Continuous effective interventions, including but not limited to larval source management and personal protection, are essential to achieving and maintaining low transmission, especially in irrigated areas.

Supplementary Data

Supplementary materials are available at *The Journal of Infectious Diseases* online. Consisting of data provided by the authors to benefit the reader, the posted materials are not copyedited and are the sole responsibility of the authors, so questions or comments should be addressed to the corresponding author.

Notes

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