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Winnie A. Lema
winnielema97@gmail.com
Ifakara Health Institute
Naomi H. Urio
Ifakara Health Institute
Dickson S. Msaky
Ifakara Health Institute
Emmanuel E. Hape
Ifakara Health Institute
Frank M. Jackson
Ifakara Health Institute
Yeromin P. Mlacha
Nelson Mandela African Institution of Science and Technology
Esther G. Kimaro
Nelson Mandela African Institution of Science and Technology
Fredros O. Okumu
Ifakara Health Institute
Halfan S. Ngowo
Ifakara Health Institute

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The role of nuisance biting in sustaining bed net adherence in south-eastern Tanzania

Winnie A. Lema[1,2], Naomi H. Urio[1,4], Dickson S. Msaky[1], Emmanuel E. Hape[1,3], Frank M. Jackson[1,3], Yeromin P. Mlacha[1,2], Esther G. Kimaro[2], Fredros O. Okumu[1,4] and Halfan S. Ngowo[1,5].

1. Environmental Health and Ecological Science Department, Ifakara Health Institute, Ifakara, Tanzania.
2. School of Life Sciences and Bioengineering, Health and Biomedical Sciences, The Nelson Mandela African Institution of Sciences and Technology, Arusha, Tanzania.
3. Wits Research Institute for Malaria, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa.
4. School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow, Glasgow, UK.
5. Institute for Disease Modelling, Gates Foundation, Seattle, USA.

- Corresponding authors: winnielema97@gmail.com; hngowo@ihi.or.tz

Email addresses:

Winnie A. Lema: winnielema97@gmail.com
Naomi H. Urio: nurio@ihi.or.tz
Dickson S. Msaky: dmsacky@ihi.or.tz
Emmanuel E. Hape: ehape@ihi.or.tz
Frank M. Jackson: frankjacksonm015@gmail.com
Yeromin P. Mlacha: ymlacha@ihi.or.tz
Esther G. Kimaro: esther.kimaro@nmaist.ac.tz
Fredros O. Okumu: fredros@ihi.or.tz
Halfan S. Ngowo: hngowo@ihi.or.tz

Abstract

Background: Consistent use of insecticide-treated nets (ITNs) is a core malaria vector-control intervention, yet adherence depends not only on perceived transmission risk but also on other factors such as thermal comfort (indoor temperature) and biting intensity (including nuisance bites from non-vector mosquitoes) but also access to and condition of the ITNs. In rural south-eastern Tanzania, ITN use remains high even in seasons of low malaria transmission, and similarly high use is reported in low-transmission urban settings, a pattern that risk-perception models cannot fully explain. Here, we tested whether nuisance mosquito biting is associated with this sustained adherence during low-transmission periods in the Kilombero valley, South-eastern, Tanzania.

Methods: Using data from 21 months of entomological surveillance and repeated household observations of ITN use, a Bayesian autoregressive logistic model and applied counterfactual attribution analysis were fitted to estimate the contribution of nuisance biting to sustained net use. This quantitative analysis was complemented by 20 in-depth interviews with community members and district health officials.

Results: Culicine mosquitoes, predominantly *Culex* and *Mansonia* species, outnumbered *Anopheles* 2.4- to 63.8-fold. Although *Anopheles* densities fell by over 98% in the 2025 dry season, ITN use remained high (83-99%) among net-owning households. Culicine densities were modestly associated with persistent ITN use in dry season (β=0.59, 95% CrI 0.26, 0.92), but no such association was observed for *Anopheles* densities (β=0.12, -0.27, 0.51). Entrenched household habits (evidenced by previous use of ITNs) also predicted current use (β=0.35, 0.01–0.90). Unexpectedly, the culicine-by-dry-season interaction was negative (β = -0.20, 95% CrI -0.36 to -0.04), indicating that the association was attenuated, not amplified, in the dry season. Counterfactual removal of culicines reduced predicted mean dry season use from 89% to 79%, a maximum attributable fraction of 11% (95% CrI 0, 25%). The interviews confirmed that nuisance avoidance, sleep comfort, and adherence to nightly household routines motivated ITN use in both seasons, whereas inability to replace damaged nets was the leading barrier.

Conclusion: Sustained ITN use in the Kilombero Valley is not explained by malaria risk alone. Use remained high after *Anopheles* densities collapsed and was modestly associated with culicine nuisance biting, nightly household routines, and sleep comfort but not densities of *Anopheles* vectors. Messaging to sustain adherence should therefore consider both comfort and nuisance relief alongside disease prevention outcomes, and should address the cost of replacing worn nets.

Keywords: Habit, nuisance, culicine, *Anopheles*, *Culex, mansonia,* Bayesian model, Insecticide treated nets, south-eastern and Tanzania.

Introduction

Insecticide treated nets (ITNs) remain a cornerstone of global malaria vector control and account for the largest share of malaria cases averted across sub-Saharan Africa since 2000 [1,2]. Their epidemiological impact, however, depends not only on ownership but also on consistent use by people most exposed [3,4]. Prevailing behavioural accounts of that use, most explicitly the Health Belief Model, treat perceived malaria risk as its proximate driver [5,6]. This framing predicts adherence as a function of transmission patterns, with peak use occurring when mosquito densities and perceived risk are highest [7]. However, empirical evidence from African countries does not bear this out, as net use frequently decoupled from transmission intensity [8,9].

The Kilombero Valley in south-eastern Tanzania is a well-suited setting in which to examine that decoupling. The area was historically subject to intense perennial transmission driven by *Anopheles gambiae sensu lato* and *Anopheles funestus*, but has undergone substantial shifts in vector composition and transmission intensity under sustained ITN coverage [10–12]. Alongside malaria vectors, the valley also supports large year-round populations of culicines, principally *Culex* and *Mansonia* spp, with the word "nuisance" commonly used to denote perceived biting burden rather than epidemiological irrelevance [13,14]. Species such as the house mosquito, *Culex pipiens quinquefasciatus*, a

key vector of *Wuchereria bancrofti* in East Africa and *Mansonia* spp., which has been implicated in filarial transmission [15], though abundant in the valley are mostly recognized for their biting nuisance.

Malaria transmission in most settings is strongly seasonal, with dry-season contraction of larval habitat sharply reducing densities of rain-dependent *Anopheles* species, notably *An. arabiensis* [16,17]. Risk-based frameworks therefore often predict a corresponding fall in net use [6], but field observations also show that adherence among net-owning households can remain high and stable through these low-risk months [13,18].

We hypothesized that this persistently high net use may be driven by immediate discomfort of being bitten by different mosquito species. Sleeping under a net therefore delivers an immediate, perceptible return in the form of undisturbed sleep, independent of any belief about malaria. On this account an ITN functions simultaneously as a disease-prevention tool and a comfort technology, and nuisance biting becomes a driver of sustained adherence that adherence studies rarely measure [19,20]. Another important factor is high night-time temperatures, which is consistently reported to reduce net use [21–23]. Bed net use is also substantially routinized, and having used a net one night is among the strongest predictors of using it the next [20,24].

In this study, we tested whether nuisance mosquito biting explains sustained net use during low-transmission periods in the Kilombero Valley, Tanzania. A Bayesian time-series model fitted to 21 months of entomological, behavioural, and environmental data estimated the contributions of culicine abundance, *Anopheles* abundance, temperature, and habit (behavioural inertia), and counterfactual simulation gave the fraction of dry-season use attributable to nuisance biting. Interviews with community members and district health officials explained the associations and the risk that suppressing nuisance biters could weaken a reason to keep using nets while residual transmission persists.

Methods

Study setting

The study ran from February 2024 to October 2025 in 23 villages of the Kilombero Valley, south-eastern Tanzania (Figure 1), nested within a larger longitudinal study. Malaria is endemic, and ITNs are distributed through mass campaigns, the School Net Program (SNP), and Reproductive and Child Health (RCH) clinics [25–27]. Seasonality is pronounced: a wet season from December to June, peaking in March and April, and a prolonged dry season from July to November, when *Anopheles* densities fall sharply [11,17,28]. Culicines, by contrast, remain abundant year-round, including when malaria vectors are nearly absent [13,14].

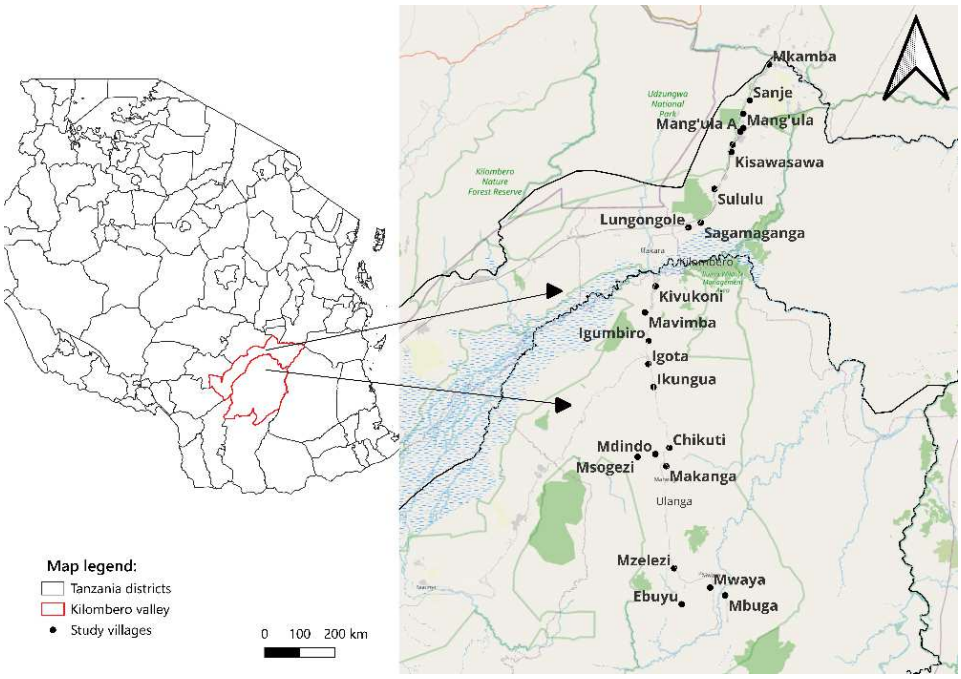


Figure 1: A map of Tanzania showing the study setting in the Kilombero Valley: Source: Open Street Map

Mosquito surveillance

Mosquito abundance was monitored monthly using CDC light traps set indoors in 12 households per village on 14 nights per month. *Anopheles* were identified to species or species complex, using morphological keys [29], and culicines were identified to genus. Malaria vectors (*An. gambiae complex*, *An. funestus* group, *An. coustani, An. squamosus, An. maculipalpus, An. ziemanni*) and culicines (*Culex* spp., *Mansonia* spp., *Aedes* spp.) were enumerated separately. Sibling species within the *An. gambiae* complex and the *An. funestus* group were not resolved molecularly.

Monthly *Anopheles* abundance and culicine abundance were summarized as the mean number of females per trap-night across all houses. Light-trap catches index indoor host-seeking density rather than human biting rates; no trap-to-landing conversion was applied, so all values are reported as mosquitoes per trap-night. Because *Aedes* spp. bite predominantly by day, they were excluded from the analysis. A sensitivity analysis excluding them from the culicine total is reported in the supplement.

Observation of bed net usage

Use of bed nets was recorded by direct observation in the same households as entomological surveillance. In each household, a trained resident observer documented all human behaviour, including net use, from 18:00 h until all members had retired. Following WHO convention, net use for a household-night was scored as a binary indicator, recorded as used if any child in the household was observed under a net at any point during the night. Child net use served as the household-level proxy for ITN adherence, being the most consistently observable indicator of household protective behaviour in field studies. This measure thus reflects household adherence rather than individual child use.

Environmental covariate

Monthly daytime land surface temperature (LST) over the study area was extracted from the MODIS for February 2024 to October 2025, matching the entomological and behavioural series [30]. Monthly mean LST was standardized to zero mean and unit variance before modelling.

Bayesian model

We specified a Bayesian autoregressive logistic model to estimate the independent contributions of *Anopheles* abundance, culicine abundance, ambient temperature, and behavioural habit to household-level ITN adherence. The response at month t was Y_t , the number of household-nights on which net use was recorded, modelled as a binomial draw from a latent usage probability U_t:

$$Y_t \sim \text{Binomial}\,(n_t, U_t)$$

Where n_t is the number of household-nights observed in month t. The latent probability was linked to predictors on the logit scale:

$$\text{logit}(U_t) = \beta_0 + \beta_{\text{mal}} \ln(Anopheles_t + 1) + \left(\beta_{\text{nui}} + \beta_{\text{nui:dry}} \cdot 1_{\text{dry},t}\right) \ln(Culicine_t + 1) + \beta_{\text{temp}} \cdot \text{Temperature}_t + \beta_{\text{habit}} \cdot U_{t-1}$$

Mosquito abundances were entered on the natural-log scale to reflect diminishing marginal response to increasing biting pressure. Temperature_t is the standardized monthly LST, and $1_{\text{dry},t}$ indicates dry-season months (July-November). The interaction term $\beta_{\text{nui:dry}}$ tests whether the culicine effect is amplified during the dry season, when *Anopheles* abundance provides little motivation for net use. The autoregressive term $\beta_{\text{habit}} \cdot U_{t-1}$ encode behavioral persistence: households that used nets last month are more likely to do so this month, independently of current exposure. It enters on the probability scale, so with β_{habit} bounded in (0, 1) it contributes a damped shift of between 0 and 1 logit units.

Regression coefficients received weakly informative normal priors with mean 0 and precision 0.1. The habit coefficient was additionally truncated to (0,1), encoding the expectation that habit reinforces rather than suppress use and constraining persistence to the damped rather than explosive. Model adequacy was assessed by comparing posterior predictive distributions of monthly usage with the observed series (Figure 2B). The full model schematic is given in Supplementary Figure S1.

Attribution analysis

To quantify the contribution of nuisance biting to observed net use, we used a counterfactual approach. For each posterior draw we computed predicted usage under two scenarios: the observed culicine trajectory, and a counterfactual in which culicine abundance was set to zero throughout, which also zeroes the interaction term. Both trajectories were propagated forward simultaneously through the autoregressive habit term, so that habit-compounding of past nuisance exposure is reflected in the estimate. The difference between trajectories is the usage attributable to nuisance biting, reported in absolute terms (percentage points of usage probability) and in relative terms (the fiction of predicted usage accounted for by nuisance biting). For the primary dry-season summary, attribution was computed for each dry-season month separately within each posterior draw and then averaged across months., yielding a posterior distribution of mean dry-season attribution that accounts for heterogeneity in culicine abundance and covariate values across those months. Because culicines were never absent during the study, setting their abundance to zero extrapolate beyond the observed data, and the resulting estimate is an upper bound.

Model fitting

The model was fitted by Markov chain Monte Carlo (MCMC) in JAGS 4.3.2 [31] called from R 4.5.1 [32] via the *runjags* and *rjags* package [33,34]. Three chains were run with 3,000

warm-up iterations followed by 10,000 posterior samples each, thinned by a factor of 5, yielding 6,000 draws for inference. Convergence was assessed by visual inspection of trace plots and the Gelman-Rubin potential scale-reduction factor with $\hat{R} < 1.01$ for all parameters. Posterior summaries are reported as means with 95% equal-tailed credible intervals. Analysis and plotting used the *tidyverse* [35], including *dplyr* [36] and *ggplot2* [37] together with *coda* [38] and *patchwork* [39].

Qualitative data collection: in-depth interviews

To contextualize the quantitative findings, in-depth interviews were conducted with two purposively sampled groups: 12 community members (R1 - R12) and eight district health officials (P1 - P8). Community members were eligible if they were aged 18 years or older and owned and used a bed net; officials were eligible if they had lived and worked in the study community for more than one year. Interviews were conducted by the first author, who has no prior relationship with participant assisted by the second author. Semi-structured guides covered perceptions of mosquito exposure, motivation for and barriers to bed net use, and strategies for sustaining adherence. Interviews were conducted in Swahili, in person with community members and in person or via Zoom with district officials. Each lasted up to 35 minutes and was audio-recorded, transcribed verbatim and then translated into English for analysis. Transcripts and field notes were analysed thematically in NVivo 14. Coding was inductive and conducted independently by two coders; saturation was judged to have been reached when no new themes emerged in the final interviews. The qualitative component is reported in accordance with the Consolidated Criteria for Reporting Qualitative Research (COREQ) checklist [40].

Results

Seasonal mosquito abundance and net usage

Across the 21-month study period, indoor CDC light-trap catches were dominated by culicines, which outnumbered *Anopheles* by 2.4- to 63.8-fold in every month (Figure 2A). The mean nightly abundance of culicine mosquitoes peaked at approximately 29 mosquitoes per trap-night, against an *Anopheles* study peak of just 6 per trap-night in August 2024. *Anopheles* abundance was lowest in the dry seasons, falling to 0.07 per trap-night in September 2025, a reduction of more than 98% from the August 2024 peak. Culicine abundance then declined overall, to about 1 mosquito per trap-night by October 2025, with temporary rises in August 2024 (about 12) and May 2025 (about 15). Among households owning at least one bed net, the observed usage remained between 83% and 99% throughout the year, including through the 2025 dry season when *Anopheles* were nearly absent (Figure 2B). The fitted model tracked the observed series closely, while the no-nuisance counterfactual ran consistently below it, most markedly during dry-season months (Figure 2B).

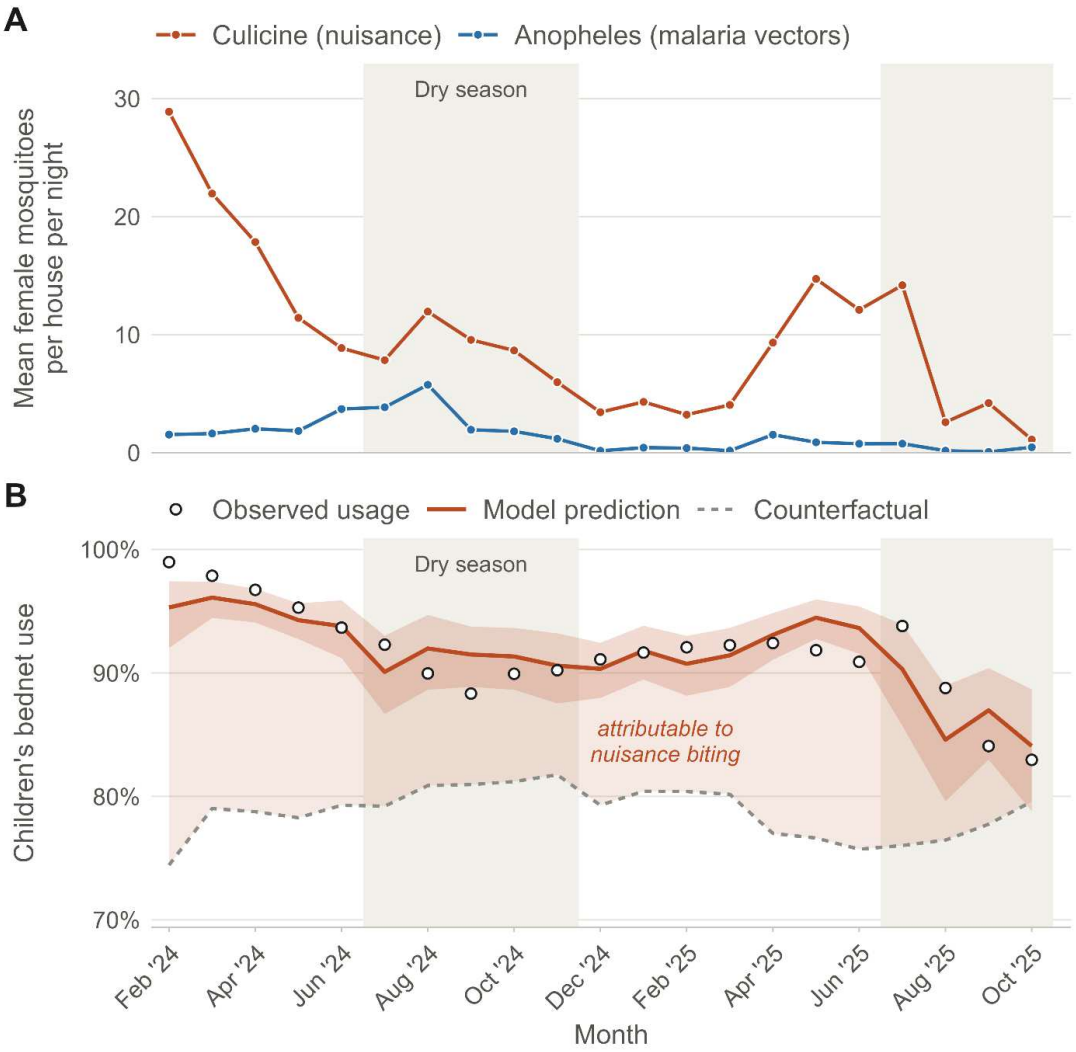


Figure 2: Seasonal dynamics of mosquito abundance and bed net use in the Kilombero Valley, Tanzania. **(A)** Monthly mean abundance of female *Anopheles* (*An. gambiae* s.l and *An. funestus* group) and culicines from indoor CDC light-trap collections, expressed as mosquitoes per trap-night. **(B)** Observed household bed net use (proportion of household-nights on which a child was observed under a net), he fitted trajectory from the Bayesian autoregressive logistic model, and the no-nuisance counterfactual in which culicine abundance is set to zero throughout. Shaded ribbons shows 95% credible intervals; grey vertical bands mark dry-season month (July – November).

Posterior coefficients estimate

Culicine abundance was the only environmental predictor for which the 95% credible interval excluded zero (β_{nui} = 0.58 CrI [0.24, 0.92]; Figure 3): higher culicine abundance was associated with greater net use across all months. The *Anopheles* coefficient was positive but imprecise (β_{mal} = 0.12 [-0.27, 0.51]), as expected given that *Anopheles* abundance was near zero for roughly half the series, leaving little contrast from which to identify a separate vector effect. Temperature was likewise indistinguishable from zero ($\beta_{\mathrm{temp}} = 0.11$ [-0.07, 0.28]).

Contrary to our directional prediction, the nuisance-by-dry-season interaction was negative (($\beta_{\mathrm{nui:dry}}$ = −0.20 [-0.36, −0.04]), indicating that the association between culicine abundance and net use was weaker during the dry season than during the wet seasons, rather than amplified. The habit coefficient was positive 0.34 CrI [0.01, 0.90], consistent with month-to-month persistence in net use independent of contemporaneous entomological and thermal conditions.

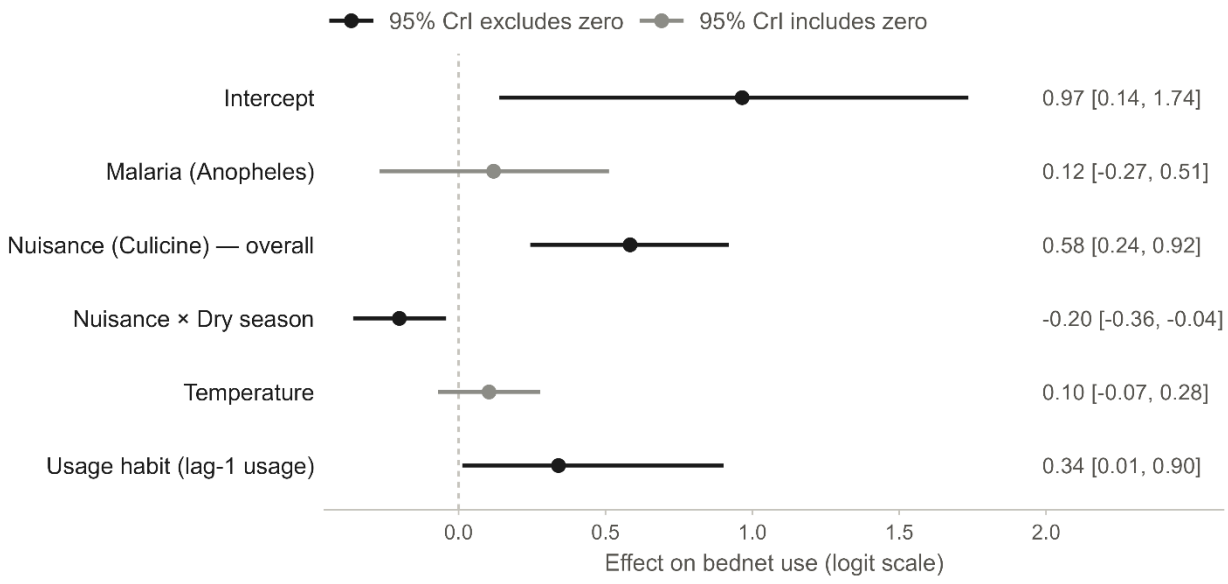


Figure 3: Posterior coefficient estimates from Bayesian model of household bed net use. Points show posterior means

Dynamic attribution of nuisance biting

Absolute attribution tracked culicine abundance, peaking at 21.1 pp in February 2024, recovering to 18.0 pp in June 2025, then falling to 4.7 pp in October 2025, when both mosquito groups were largely absent (Figure 4A). Dry-season months averaged 9.9 pp against 15.2 pp in wet-season months, with overlapping ranges. The same pattern held on the relative scale, where culicine biting accounted for 5.6–22.0% of predicted use (Figure 4B).

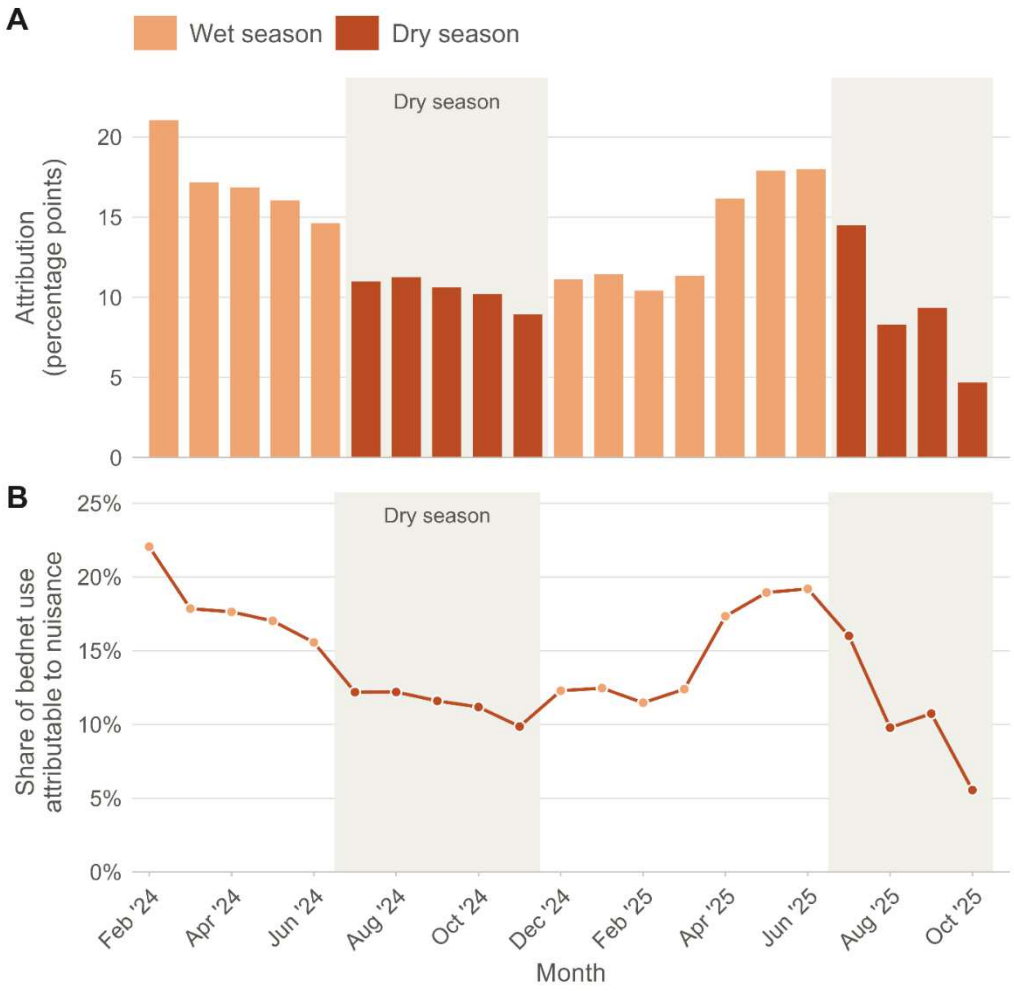


Figure 4: Absolute nuisance attribution in bed-net usage from non-malaria bites (A) and fraction of bed net usage attributable to nuisance bites (B) observed from February 2024 to October 2025 in Kilombero Valley.

Using the full joint posterior across the nine dry-season months (July–November 2024 and July–October 2025), a mean of 11.1% (95% CrI −0.2 to 26.3%) of dry-season bed net use

was attributable to culicine biting (Figure 5A). The lower bound reaches zero, so the data remains compatible with a negligible contribution as well as with a substantial one. On the absolute scale, the model predicted mean dry-season usage of 89.1% (95% CrI 87.0–90.9%) with culicine biting present, against 79.2% (95% CrI 65.5–89.4%) under complete removal, a difference of only 9.8 percentage points (Figure 5B). The wide counterfactual interval reflects the extrapolation required to remove a genus that was never absent from the study setting.

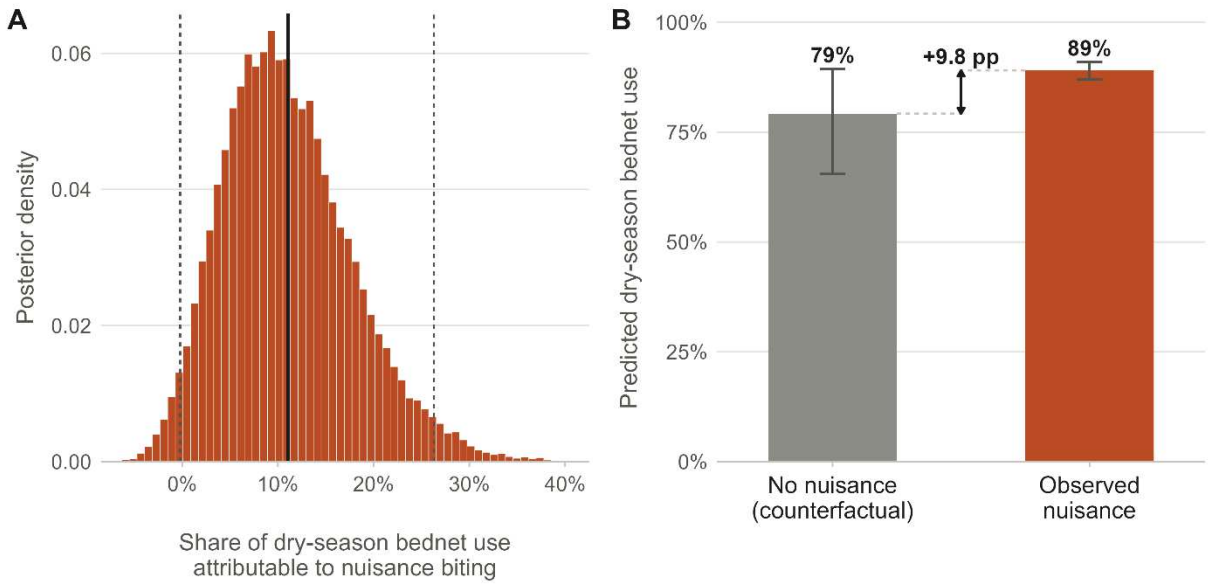


Figure 5: Posterior estimates of dry-season bed net use attributable to nuisance (culicine) biting, averaged across nine dry-season months (July-November 2024 and July-October 2025). (A) Posterior distribution of the mean dry-season attributable fraction; the point shows the posterior mean (11.1%) with 95% credible interval (0–25%) as error bars. (B) Counterfactual comparison of mean predicted dry-season bed net use with observed culicine biting present versus a counterfactual scenario in which culicine abundance is set to zero throughout (complete removal); error bars show 95% credible intervals.

Community perceptions regarding year-round mosquito exposure in sustaining consistent bed net use.

A total of 20 in-depth interviews were conducted, eight with district officials and 12 with community members from the study villages. Inductive approach was applied to generate five major themes as shown in Table 1 below;

Table 1: Main thematic analysis results summaries: In-depth interviews with Community members and District officials.

Category	Themes and contributing explanations identified during in-depth interviews	
	Main themes	Sub themes
Mosquito exposure	Perceptions of Continuous but Fluctuating Mosquito Exposure	Mosquito presence perceived as year-round but variable Seasonal peaks linked to rainfall and agriculture Permanent habitat-creating activities
Reasons for bed net use and beliefs about malaria	Nuisance avoidance and undisturbed sleep as primary drivers of year round adherence	Awareness of malaria and other diseases Comfort and annoyance prevention Habit Mosquito density (as motivator)
Actual behaviour and seasonal triggers	Seasonal and social factors undermining consistent adherence	Heat and discomfort Negative beliefs and misconceptions Other net uses (repurposing) Seasonal mosquito decline Social practices
Net condition, access, and affordability	Economic constrains that prevent the translation of risk awareness into consistent net ownership	Affordability Net deterioration and durability Net insufficiency, condition and household size Reliability and timely distribution Limited resources Low community participation Improper usage /reporting Untreated nets
Community views and recommendations	Proposed strategies to sustain net adherence during low transmission periods	Health education Increasing accessibility Improving tracking system Governmental sustainable system Environmental management Insecticide treatment tablets Comprehensive studies

Perceptions of continuous but fluctuating seasonal mosquito exposure

Participants from both groups consistently described mosquito presence as a year-round problem in the Kilombero valley and surrounding areas, while acknowledging that density varies considerably by season, geography, and human activity such as brick making, irrigation farming, road construction, mining, vegetable cultivation, and waste disposal. Peak periods were associated with rainfall and agriculture, but participants were evident that mosquitoes never fully disappear.

"Mosquitoes are present all year round, but in some months, they decrease in number while in others they increase. For me there's no difference. I use a mosquito net in every season because where I live mosquitoes never completely disappear."- R2

"Malaria transmission is seasonal, with two main peak periods that align with agricultural seasons particularly at the beginning and after farming activities. These peaks typically occur between March and April, and again from July to October."- P1

Nuisance avoidance and undisturbed sleep as primary drivers of year-round adherence

Across both groups, awareness of malaria risk was near-universal, seven of eight district officials and all twelve community members described malaria risk as well understood and deeply embedded in community consciousness, shaped by decades of sensitization campaigns, school-based health education, antenatal services, and direct observation of the disease's consequences.

"The main reason is that many past studies showed clearly that our valley has many malaria-transmitting mosquitoes. People now understand this, and because malaria is a serious threat to human life, they are motivated to protect themselves."- P5

However, this awareness functioned as background knowledge rather than the proximate driver of nightly net use. When participants explained why they actually used a net on a given night, nuisance mosquito biting and the need for undisturbed sleep were described

as the more immediate and consistently cited motivation. Mosquito nuisance was identified by all eight district officials and more than half of community members (eight of twelve) as a powerful, standalone driver of adherence, independent of disease concern. District officials emphasized that biting and buzzing mosquitoes disrupt sleep in ways that motivate net use even among community members with limited knowledge of disease while community members cemented this by explaining the discomfort caused by other non-mosquito insects like moths, lizards and others.

"Once inside the net I would sleep comfortably and the night would pass quickly. But without a net you cannot sleep peacefully because mosquitoes keep disturbing you, so the night feels very long."- R7

"··· mosquitoes are very troublesome the bites itch a lot so in the end people use nets. Even if you told someone not to use a bed net, they might not understand because they believe that even without malaria, the itching from mosquito bites is unbearable." - P7

Less than quarter of all participants noted that habitual use reinforces adherence over time. In areas with consistently high mosquito density such as the Kilombero Valley, bed net use has become normalized to the point where it continues regardless of seasonal fluctuations.

Other reinforcing factors cited included continuous health education and direct experience with malaria including witnessing the financial burden and mortality associated with the disease, availability of nets through mass distribution campaigns, antenatal clinics, school programs, and availability of private markets.

Seasonal and social dynamics that undermine consistent daily use adherence

Despite widespread awareness and generally positive attitudes towards bed nets, participants across both groups described a range of factors that create inconsistency in use. These factors include seasonal heat, perceived seasonal declines in mosquito density, social

and cultural practices. District officials described sleeping outdoors during communal events such as funerals, or during agricultural migration, reduces both access to nets and the social expectation of using bed nets.

"During hotter months like August, September, and October, even though mosquitoes are still present, people often sleep outdoors due to heat and may neglect using nets." - P2

"Social practices such as sleeping outdoors during funerals, where using a net may be socially discouraged."-P3

Nevertheless, negative beliefs and misconceptions were mostly reported by district officials as barriers hindering the adherence. For instance, net chemicals harm health, reduce male sexual performance, or that free items are politically motivated or dangerous. Damaged or worn-out nets were also described by more than a half of all participants as being redirected towards fishing, garden fencing, poultry keeping, crop protection, and covering windows, a pattern observed across multiple participant sites.

"Some misconceptions also persist, such as beliefs that nets reduce male strength." - P3

Economic constraints that prevent the translation of risk awareness into consistent net ownership

Both district officials and community members consistently described a gap between awareness of mosquito risk and the ability to maintain consistent bed net use, attributing this gap to a range of structural, economic, and systemic barriers. Economic hardship was the most frequently cited constraint by almost three quarters of all participants, unable to purchase replacement nets once existing ones deteriorate.

"If a net becomes damaged, the first thing is to look for money to buy another one. Sometimes the net is already damaged, but you do not have money. So, you continue repairing it until you can afford another one."- R1

Other least mentioned constraints include low community participation in registration exercises for distribution campaigns, supply chain issues, procurement system challenges, presence of untreated nets were identified as reducing household access. Limited funding for continuous community education, misconceptions that persist despite health education efforts, and dependency behaviours among communities accustomed to free distribution were also described as compounding structural challenges.

"One major challenge is low community participation in registration for distribution campaigns."- P2

Proposed strategies to sustain net adherence during low-transmission periods.

All district officials converged on the view that continuous health education is the most critical strategy for maintaining bed net use during periods when mosquito density and thus perceived risk appear lower. Education was also described by the community members as essential not only for initial uptake but for sustaining the understanding that mosquito exposure and malaria risk persist year-round.

"Education is essential. Without it, people would not understand the importance of nets. Over time, people observe reduced malaria cases within their households, reinforcing continued use."- P3

"It is mainly health education. When you go to the dispensary, health workers strongly emphasise that nets are important for preventing malaria. Because of that emphasis, when parents return home, they even remind their children to use nets."- R1

Schools, community meetings, posters, antenatal services, local awareness campaigns, and religious gatherings were identified as effective platforms for reinforcing sustained adherence. Children and schools were specifically highlighted as channels for strengthening net use practices within households.

"School-based distribution is also effective, as children help reinforce usage practices at home." - P2

Improving access to nets through expanded and more frequent distribution was a widely recommended strategy. Multiple participants called for distribution beyond the current mass campaign cycle, suggesting inclusion of additional antenatal visit points, school distribution, and 1:2 net per member's coverage ratios.

"We should expand free distribution programs. For example, provide nets not only at first antenatal visits and at nine months, but also include additional points such as at six months. This would increase the number of nets per household and ensure continuity." - P2

A quarter of district officials recommended longitudinal community-based research to generate more rigorous, season specific evidence on net use patterns and mosquito exposure, moving beyond experience-based knowledge towards scientific data.

"More longitudinal research conducted over an entire year would provide clearer, evidence-based insights, as much of our current understanding is based on experience rather than scientific evidence." - P1

Discussion

ITN adherence in the Kilombero Valley remained high throughout the dry season, when malaria transmission was negligible, a pattern that standard risk-based frameworks, which predict use to track transmission intensity, do not accommodate. Across the 21month, culicine abundance was the only environmental covariate whose credible was distinguishable from zero, while *Anopheles* coefficient could not be distinguishable. This asymmetry is not evidence that nuisance biting matters more than vector biting: *Anopheles* densities were near zero for roughly half the series, affording little contrast with which to

identify a separate vector effect, and the two abundance series are themselves seasonally correlated. What the data support is that a driver unrelated to malaria risk was associated with sustained use. That is consistent with findings from Dar es Salaam, where residents cited biting discomfort rather than disease concern as their primary reason for using nets [19], and from Benin, where nuisance-driven adherence persisted through low-transmission periods [18].

These results offer a partial explanation for the persistence of high use (83-99%) through the 2025 dry season, when *Anopheles* abundance fell to 0.07 mosquitoes per trap-night, more than 98% below the study peak. Under risk-based account adherence should have fallen with it, as documented in Tororo, Uganda, following sustained malaria control [22]. In Kilombero, culicines instead maintained a 2.4-63.8-fold excess over *Anopheles* in indoor catches across dry-season months, sustaining a biting burden that persisted when vector-borne risk did not. *Culex quinquefasciatus* has been reported to contribute up to 79% of indoor nuisance biting year-round in adjacent Ulanga district [14], but because culicines were identified only to genus here, that composition is assumed rather than demonstrated, and the relative contributions of *Culex* and *Mansonia* remain unresolved.

The nuisance effect was not uniform across the year. The interaction term was negative, indicating that culicine abundance was less predictive of net use during the dry season than during the wet season. This is a change in association, not a fall in adherence: observed use remained within 83-99% throughout. One candidate explanation comes from the interviews, in which district officials described people sleeping outdoors during the hot months of August to October, where nets are neither available nor socially expected. Our temperature covariate was too coarse to test this, so the mechanism remains unresolved. Reduced perceived need during low-density months is a further possibility, consistent with reports of caretakers questioning the need for net once transmission declined in Zanzibar [41].

Behavioural persistence also contributed. The habit coefficient was positive, indicating that use in one month predicted use in the next independently of contemporaneous entomological and thermal conditions. This is consistent with evidence that prior net use is among the strongest predictors of subsequent use, and that adherence becomes routinized over time [24], a mechanism that helps explain why observed use remained stable across seasons in which mosquito exposure changed substantially. Thermal discomfort, by contrast, is among the most consistently reported barriers to net use [21,23], but monthly satellite land surface temperature is a coarse surrogate for indoor sleeping-space temperatures, and our null coefficient is uninformative about that trade-off rather than evidence against it.

The findings bear on how vector control is monitored. Current interventions in Tanzania, including dual-active-ingredient ITNs and larval source management, suppress mosquito populations broadly [2,42,43]. Such suppression is necessary and effective, but reducing nuisance biting alongside vectors could erode a comfort-driven motivation for net use while residual transmission persist [42,44], an effect current programme monitoring is not designed to detect. This is a monitoring and messaging problem, not a trade-off in vector control. Culicine suppression should not be deprioritised to preserve a behavioural incentive: *Culex quinquefasciatus* is the principal vector of *Wuchereria bancrofti* in East Africa [15], nuisance biting imposes a genuine burden on sleep and wellbeing and retaining it would be inconsistent with lymphatic filariasis elimination goals. The appropriate response to a weakening sensory cue is to strengthen the substitute cue through communication and access.

The qualitative findings indicate where that communication could be aimed. Malaria programmes typically foreground disease prevention, yet both community members and district officials described immediate benefits like relief from biting, undisturbed sleep as the more salient motivators [19,20]. Messaging that acknowledges these benefits alongside

457 disease prevention, and that reinforces year-round exposure, may align better with the
458 reasons people give for using nets. Structural barriers require parallel attention: economic
459 constraint, particularly the inability to replace deteriorated nets, was the most frequently
460 cited barrier in our interviews and severs the link between risk awareness and protective
461 behaviour regardless of how well informed a household is [23,45].

462 Several limitations qualify these findings. Net use was recorded by household members who
463 knew that use was being observed, so adherence may be inflated by reactivity; this should
464 bias the intercept upward without distorting the month-to-month covariation on which the
465 model relies. The outcome was scored as used if any child was observed under a net at any
466 point in the night – a permissive definition that approaches a ceiling in high coverage
467 settings, and the resulting compression (83-99%) limits the variance available to identify
468 covariate effects, bearing directly on the null *Anopheles* and temperature coefficients [4].
469 The model was fitted to 21 monthly proportions, discarding household and village-level
470 heterogeneity and leaving 21 time points for six parameters; a hierarchical binomial model
471 with village-level random effects fitted to the household-night data would use the
472 information more efficiently. Monthly resolution also limits detection of short-term variation,
473 and temperature was modelled as a linear term, a quadratic specification being untestable
474 at this number of time points. Low vector densities for much of the study further reduced
475 power to estimate the *Anopheles* contribution. The study covers a single ecology with
476 unusually high nuisance densities, which may limit generalizability [13,46], and the qualitative
477 component comprised twenty purposively sampled interviews, illustrative of motivations and
478 barriers rather than representative of their prevalence. Finally, the counterfactual assumes
479 complete removal of culicines, a scenario beyond the observed data, so the attributable
480 fraction is an upper bound.

Experimental or quasi-experimental design are needed to test whether nuisance biting causally sustains adherence. Nightly measurement of biting exposure, indoor temperature, and net use would resolve questions that monthly aggregation cannot, and comparison across ecologies with differing culicine burdens would establish generalizability. Incorporating behavioural drivers into transmission models may improve predictions of intervention impact as mosquito communities change [42,44].

Conclusion

In a setting where culicines outnumbered malaria vectors throughout the study, nuisance biting was the only environmental factor credibly associated with net use. Counterfactual modelling suggests it may account for a modest share of dry-season use (11%), although the interval extends to zero. Previous use (habit) was also associated with current use. Sustained adherence is therefore not explained by malaria risk alone. Control measures that reduce nuisance mosquitoes as a by-product may weaken one reason for using nets, which is a reason to anticipate and offset that effect, not to tolerate nuisance biting. Health messaging should pair the comfort benefits of nets with disease prevention, and programmes should address the cost of replacing worn nets through wider and more equitable distribution, so that motivated households can keep continuous protection.

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drafted the manuscript. FMJ, EEH, NHU, DSM, YPM, EGK and FOO were involved in reviewing the manuscript. HSN reviewed the manuscripts and provided supervision throughout. All authors read and approved of the final manuscript.

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Availability of data and materials: All data generated and supporting the conclusions of this manuscript have been included in this article. Raw data and material are available from the corresponding author upon request (WAL).

Declarations

Ethics approval and consent to participate: Approvals for this study was obtained from the Ifakara Health Institute Institutional Review Board (IHI/IRB)-IHI/IRB/EXT/No:36-2025 and the National Institute for Medical Research of Tanzania (NIMR)-(NIMR/HQ/R.8c/Vol, I/2844) prior to data collection. Written informed consent was obtained from all participants before their involvement in the study, and all methods were carried out in accordance with the Declaration of Helsinki. Confidentiality was maintained by assigning unique identifiers to all participants (both community members and district officials) in place of names across all transcripts and outputs. For the quantitative component, household-level consent was obtained from designated representatives. No biological samples were collected from human participants, as mosquito surveillance relied exclusively on CDC light traps.

Consent for publication: Permission to publish this study was obtained from NIMR (ref. no).

Competing interests: The authors declare that they have no competing interests

Abbreviations:

AF	Attributable fraction
An	*Anopheles*
b/p/n	Bites per person per night
CDC	Center for disease control
CrI	Credible Interval
DVCO	District Vector Control Officer
HBM	Health Belief Model
IDI	In depth Interview
IHI-IRB	Ifakara Health Institute- Institutional Review Board
JAGS	Just Another Gibbs Sampler
LLIN	Long Lasting Insecticidal Net
MCMC	Markov Chain Monte Carlo
MODIS	Moderate Resolution Imaging Spectroradiometer
NIMR	National Institute of Medical Research
NMCP	National Malaria Control Program
Pp	Percentage point
RCH	Reproductive and Child Health
SNP	School Net Program
Spp.	Species
WHO	World Health Organisation

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