Effect of a novel house design (star home) on indoor malaria mosquito abundance in rural Tanzania: secondary outcomes of an open-label, household, randomised controlled trial

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Summary

Background Screening houses can reduce malaria transmission in sub-Saharan Africa. Our study evaluated whether a novel screened house design (star home) with bedrooms on the second storey reduced indoor mosquito abundance compared with traditional houses in Mtwara, Tanzania.

Methods In this open-label, household, randomised controlled trial, indoor mosquito abundance was assessed in 110 star homes and 110 neighbouring traditional houses in 59 villages from Jan 5, 2022, to Dec 20, 2023. Mosquitoes were collected using US Centers for Disease Control light traps every 7 weeks. *Anopheles gambiae* and *Anopheles funestus* species were identified using PCR and *Plasmodium falciparum* sporozoites detected using ELISA. Nightly temperature, CO_2 concentrations, and duration of door opening was recorded. Differences between study groups were analysed using generalised linear mixed-effects models. The trial is registered with ClinicalTrials.gov (NCT04529434).

Findings Of 9290 mosquitoes collected, 1899 were *A gambiae*, 69 were *A funestus*, and 7322 *Culex* species, mainly *Culex quinquefasciatus*. Star homes had 51% less *A gambiae* (adjusted risk ratio [RR] 0·49, 95% CI 0·35 to 0·69; p<0·0001) and 61% less *Culex* species (RR 0·39, 0·32 to 0·48; p<0·0001) than traditional houses. At night, star homes were 0·5°C cooler (95% CI 0·2 to 0·9; p=0·010), with similar concentrations of CO_2 (–7 ppm, 95% CI –19 to 6; p=0·285) and had external doors open 53% less time than traditional houses (7·5 min/h *vs* 16·2 min/h; p<0·0001).

Interpretation Star homes reduced indoor mosquito abundance and malaria transmission risk compared with traditional houses, demonstrating the protective efficacy of houses that are well screened and air permeable in rural Africa.

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Introduction

Africa's population is growing rapidly,[1] projected to increase from 1·36 billion in 2020 to 2·49 billion by 2050.[2] Given that most of sub-Saharan Africa's population lives in rural areas,[3] many new houses will need to be built there, where malaria transmission is most intense.[4] Between 2000 and 2015, the prevalence of improved housing in rural sub-Saharan Africa increased from 8% to 18%, reflecting a gradual enhancement of housing quality across the region.[5] This new housing presents a crucial opportunity to construct better-quality houses that could help protect the growing population from malaria.

Mosquito-proof housing is essential because most malaria transmission in sub-Saharan Africa occurs indoors at night.[6] In traditional houses, *Anopheles gambiae* mosquitoes primarily enter through open eaves and, to a lesser extent, through gaps around windows and doors.[7] A systematic review and meta-analysis of studies from 1900 to 2013 showed that residents in modern houses had a 47% lower risk of malaria infection than those in traditional homes.[8] A Cochrane review of seven trials reported that individuals in modified houses were 32% less likely to have *Plasmodium falciparum* and 30% less likely to have anaemia than those in unmodified homes.[9] In light of this evidence, WHO now recommends house screening as a supplementary measure for malaria control, although the evidence base is scarce because of the absence of randomised controlled trials (RCTs).[10]

Integrating development interventions such as house screening with conventional biomedical tools aligns with the sustainable development goals (SDGs), particularly SDG 3 (good health and wellbeing) and SDG 11 (sustainable communities).[11] A pilot study done in northeast Tanzania in 2014–15 tested six prototype houses against mosquito entry, showing that novel-designed healthy two-storey houses reduced mosquito entry by 96% and single-storey houses by 77% compared with outdoor catches.[12] Given the success of these prototypes in reducing mosquito entry and their positive reception

Research in context

Evidence before this study

Most malaria transmission in sub-Saharan Africa occurs indoors at night. Therefore, preventing the entry of mosquitoes into houses would contribute greatly to a reduction in malaria. A Cochrane review published in 2022 (CD013398) of housing modifications for preventing malaria identified one randomised controlled trial (RCT) and seven cluster RCTs of mainly screening sometimes combined with insecticide and lure and kill devices. Overall, these house modifications reduced the prevalence of *Plasmodium* malaria infections by 32%. In all studies reported, existing houses were modified to incorporate the house interventions.

Added value of this study

The present study is the first to test the protective efficacy of a novel design of house (star home) against malaria mosquitoes in a household RCT. The houses were designed to exclude mosquitoes from entering the house, were cooler and better ventilated than traditional houses. Overall, star homes reduced the number of mosquitoes entering a house by about a half compared with traditional houses. This directly translates into a 50% reduction in malaria transmission.

Implications of all the available evidence

The population of sub-Saharan Africa will nearly double between 2020 and 2050, requiring many new homes to be built to support the growing population. These new homes should ideally share many of the features of the star homes including screened windows and doors, self-closing durable doors, bedrooms on the second storey, and built with low thermal mass materials to reduce mosquito house entry, keep the occupants cool, and reduce the carbon footprint associated with a new building.

by residents, an RCT was done to evaluate a novel two-storey house design, the star home. The primary objective was to assess the effect of star homes on childhood diseases including malaria, diarrhoeal diseases, and respiratory tract infections.

This Article presents an important secondary objective, the effect of star homes on indoor malaria mosquito abundance compared with traditional houses over 2 years. The study also examined the effects of star homes on nightly temperature, CO_2 concentration (an important attractant for malaria mosquitoes),[13] and the duration of door opening. We hypothesised that star homes would be cooler, have lower CO_2 concentrations, and have their doors open for shorter periods than traditional homes, attributes that could encourage the use of insecticide-treated nets (ITNs),[14] reduce mosquito–host interactions,[15] and prevent mosquito entry. Measuring the effect of healthy houses on indoor mosquito density with a design that was acceptable to residents of these homes was our intent. To our knowledge, this study is the first RCT of a novel house design aimed at reducing malaria transmission, with findings relevant to malaria control efforts and rural housing development in sub-Saharan Africa.

Methods

Study design

A detailed description of the study is provided by Mshamu and colleagues.[16] Briefly, this open-label, household, RCT involved a cohort of 110 star homes and 110 neighbouring traditional houses in rural Tanzania, with indoor mosquito abundance recorded every 7 weeks from Sept 14, 2021, to Dec 19, 2023. The period from Sept 14 to Dec 17, 2021 served as a preparatory phase, during which all families moved into the star homes and ITNs were distributed. Surveillance data from Jan 18, 2022, to Dec 19, 2023 are reported here, capturing the period during which star home occupants were fully protected.

The study was approved by the National Research Ethics Committee of Tanzania (registration number NIMR/HQ/R.8a/Vol.IX/3695) and the Department of Biosciences Ethics Committee, Durham University, Durham, UK (approved June 24, 2020). Study participants who provided informed consent and those who provided signed witnessed consent forms were recruited into the study. The study was done in compliance with the principles set out by the International Conference on Harmonization Good Clinical Practice, the Declaration of Helsinki, and the ethical requirements of Tanzania.

The study was done in 59 villages within the rural Mtwara region of southeast Tanzania (10·5181° south and 40·0633° east; figure 1). The area, a coastal strip of sandy low-lying land with undulating hills, reaches a maximum altitude of approximately 350 m above sea level and is covered by forest, shrubland, and cultivated land. Although a distinct rainy season exists, rainfall can occur throughout the year. The Makonde are the predominant ethnic group, followed by the Makua and Yao people. Key economic activities include the cultivation of cashew nuts, cassava, maize, and rice, with fishing also contributing to the livelihoods of residents in coastal villages.[17]

A recent study in two southern villages of the current study area, conducted during the dry season (mid-June to late July, 2019), found that *Culex quinquefasciatus*, a vector of lymphatic filariasis, was the most prevalent mosquito species (85%), with *Anopheles funestus* (0·6%) and *A gambiae* (0·1%) being relatively rare.[18] Malaria parasite prevalence in the study area exceeds 20%, particularly among children aged 6–59 months and pregnant women, with ITNs being the primary vector control tool (ownership rate, 74%; coverage, 51%).[19]

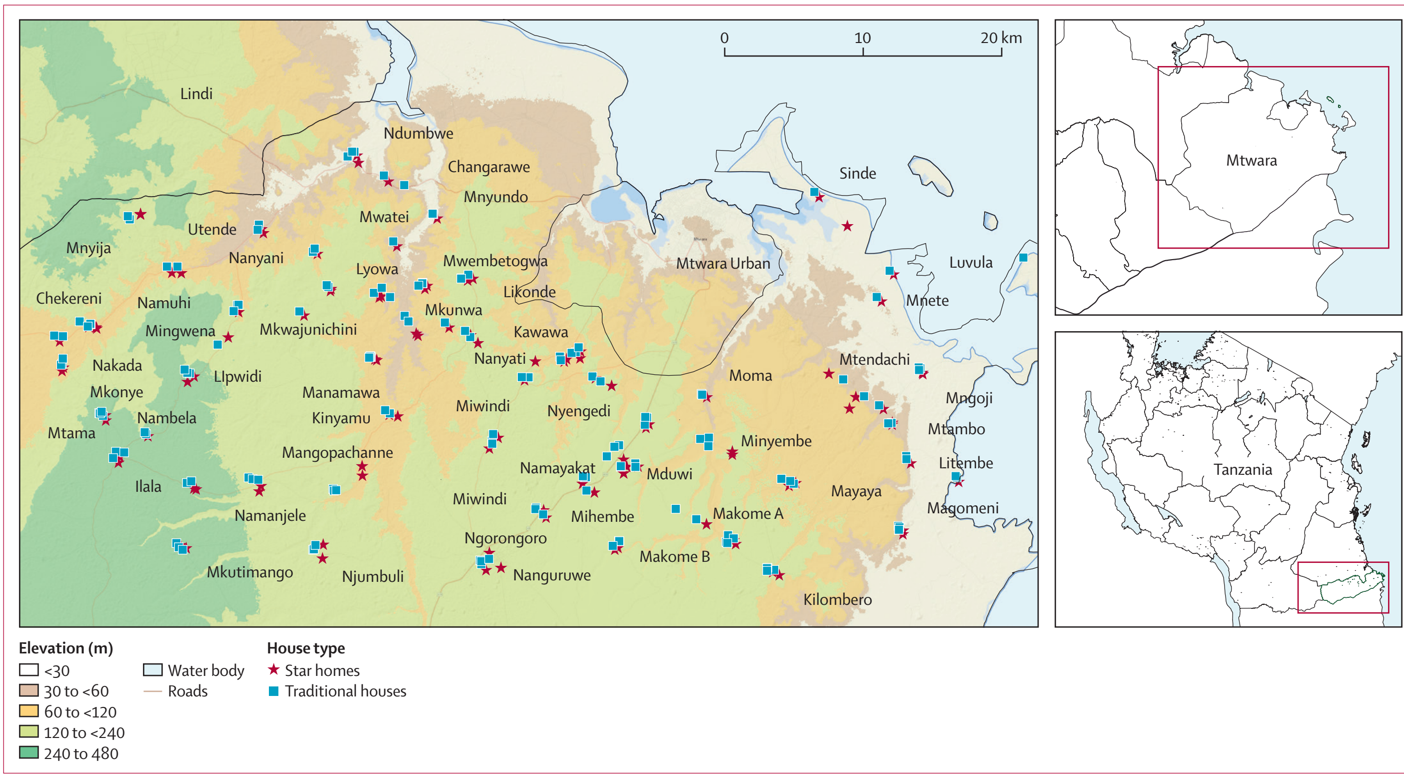

Figure 1: **Location of study houses**

Interventions

Star homes were constructed over 25 months, from June 1, 2019, to June 30, 2021 (figure 2). Each study village had between one and three star homes, each paired with a neighbouring traditional house, where the household consented to trial participation. The star homes are two-storey structures with two sleeping rooms on the second storey (figure 3A). Key features designed to reduce mosquito entry and malaria transmission included: shade cloth walls, in which the walls are made of air-permeable shade cloth, preventing mosquito entry, enhancing ventilation, reducing indoor CO_2 concentrations,[20] and potentially lowering bedroom temperatures at night, facilitating ITN use;[14] self-closing doors, which are fitted with self-closing hinges limiting mosquito entry through this route;[21] second-storey bedrooms, which required sleeping rooms to be on the second floor, perhaps reducing mosquito exposure;[22] and a screened kitchen, which requires the ground-floor kitchen to be screened, providing a communal area for evening gatherings, further reducing mosquito contact.

Two rounds of ITN distribution were done during the study: July 5, to Dec 21, 2021 and Oct 24, 2022, to Feb 24, 2023, ensuring that each net was shared by two individuals as the number of occupants increased. Each study house received two Olyset nets (2% permethrin; Sumitomo Chemical and A to Z Textile Mills, Arusha, Tanzania).

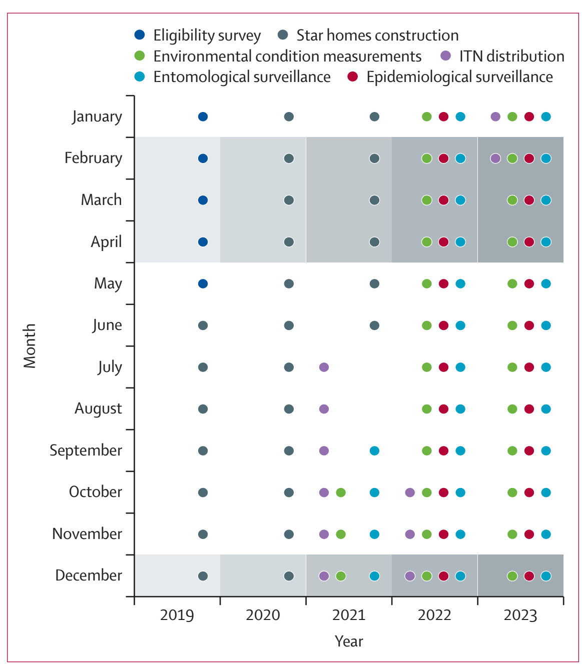

Figure 2: **Trial design**

Grey bars represent rainy seasons. ITN=insecticide-treated net.

Participants

Traditional households (figure 3B) were eligible for inclusion if the houses had mud walls, a thatched roof,

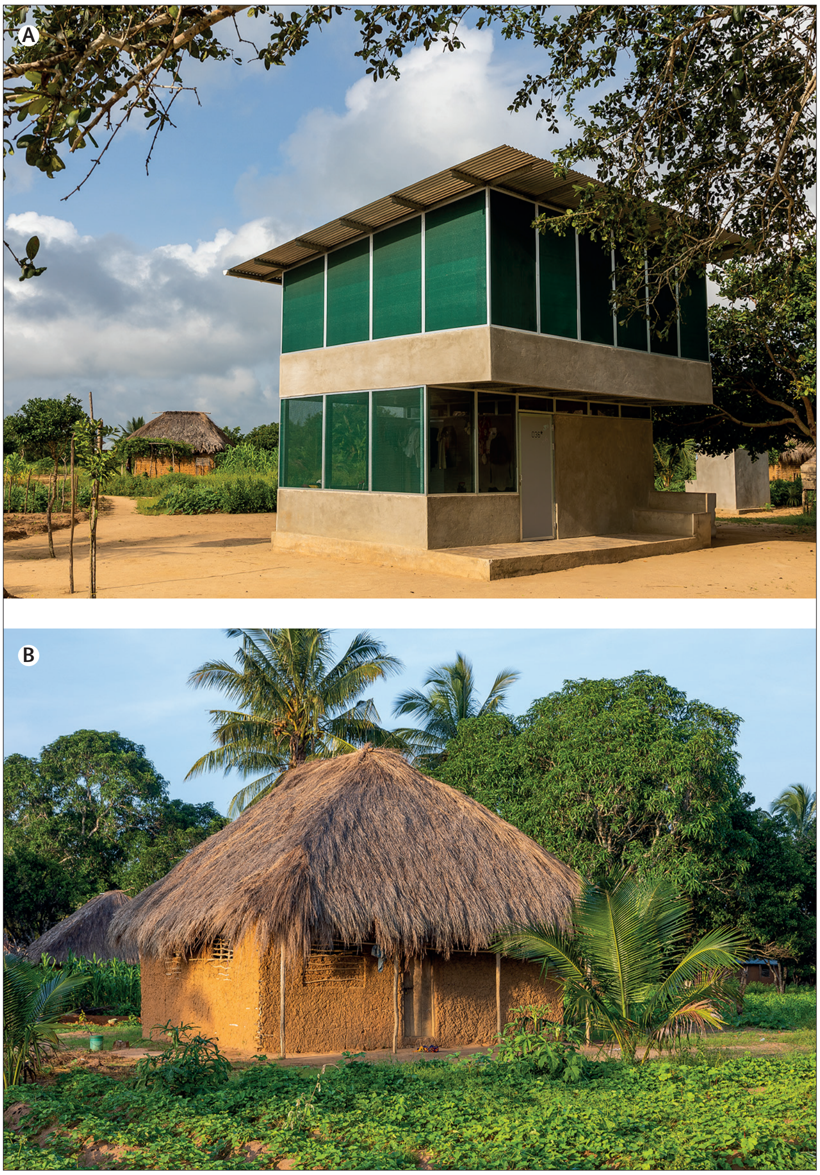

Figure 3: **Study houses**
Star home (A) and traditional house (B).

a dirt floor, a pit latrine, no grid electricity, no access to piped water, sufficient land for a new star home construction, at least two children younger than 13 years, and the householders were willing to participate in 3 years of surveillance. These criteria led to the identification of 862 eligible households, from which 110 owners of star homes were selected by lottery. The nearest 110 consenting traditional houses to each star home were selected for pairing, aiming for similar mosquito abundance around each pair.

Randomisation and masking

The study area was divided into seven geographically distinct areas. The order in which the areas were visited were randomly selected using random numbers for the first survey and this order maintained throughout the study. Six areas each contained 16 star homes and 16 control houses, and one area had 14 star homes and 14 traditional houses. Indoor host-seeking mosquitoes were sampled every 7 weeks using US Centers for Disease Control (CDC) light traps, with traps placed in rooms where at least one study child slept. As a result of the open-label design, complete masking was not possible. Bias in mosquito collection, however, was minimised by using light traps independent of fieldworker collection skills. Trap catches were analysed by different technicians not involved in the trapping process, and datasets were unmasked only after all crucial data were locked.

Outcomes

The primary outcome was the number of anopheline mosquitoes collected indoors using light traps in both study groups. Secondary outcomes were indoor night-time temperature, indoor CO_2 concentration, and duration of external door opening.

Procedures

We carried out two questionnaire surveys, from May 12 to June 12, 2022 and June 27 to Aug 8, 2023. Data were gathered using an electronic open-structured questionnaire between 1600 h and 1730 h, employing KOBO-collect software on Samsung Galaxy Tab A7 Lite (model SM-T220, made in Viet Nam). Information on the number of children and adults sleeping in the room, ITN use and type, and room construction were collected.

CDC light traps (incandescent light, Model 512; BioQuip product, California, USA) were placed 1 m above the ground at the foot end of a study child's bed, operating from 1900 h to 0700 h the following morning. Mosquitoes were killed and sorted by taxa, using established mosquito identification keys[23] and their taxa, sex, and relevant experimental design information recorded.

Because of the small number of mosquitoes collected, to validate light-trap efficiency, resting mosquito collections were done using mechanical aspirators (Prokopack, model 1419; John W Hock, Gainesville, USA)[24] in 220 star homes and 220 traditional houses from March 7 to June, 2023.

Subsamples of primary malaria vectors were identified to species using multiplex PCR to distinguish between members of the *A gambiae* complex[25] and *A funestus* complex.[26] ELISA detected the presence of circumsporozoite proteins in mosquito salivary glands (*Plasmodium* infections).[27]

Indoor and outdoor temperature and CO_2 were recorded using electronic data loggers (GasLab, CO2Meter.com, model CM-0018-AA; GasLab, FL, USA), recording every 30 min from 1900 h to 0600 h the following morning, the night after mosquito collections were made. The earlier collection time of the loggers, compared with mosquito collections, allowed field staff to collect loggers before families left to work in the fields and the homes locked up. Indoor loggers were positioned at the foot end of the child's sleeping area, 1 m above the floor (appendix p 6). Outdoor loggers were mounted on a metal stand, positioned 1 m above the ground, 5 m from the house (appendix p 6). One night each week, 12 data loggers recorded temperature and CO_2 concentrations—four in star homes, four in their corresponding four traditional houses, and in four locations outdoors.

In star homes, two-door loggers (Onset UX90-001-HOBO state pulse (Hobo data loggers, Bourne, MA, USA), HOBO On State data loggers) were installed—one on the main external door (appendix p 6) and the other placed on the internal door between the kitchen and the storeroom, near the bottom of the stairways leading to a study child's bedroom. For traditional houses, a single data logger was installed only on the main external door given that control houses lacked bedroom doors. 12 door loggers were deployed each night, with eight placed in star homes and four in traditional houses. These loggers recorded door openings every 30 s from 1900 h until 0600 h the following morning. Duration of door opening was recorded in four star homes and four traditional houses on the same night each week.

Statistical analysis

Sample size was estimated on the basis of a study done in Kilombero valley, Tanzania, in which the mean number of female *A gambiae* per trap in a house was 10·4 (SD 21·5). We used a computer simulation, based on a negative binomial distribution, and found that 110 star homes and 110 control houses would detect a 66% reduction in *A gambiae* with more than 90% power at the 5% level of significance in 1 year. We planned to sample from every star home (n=110) and the nearest control house (n=110) every 7 weeks for 2 years to allow for variation in mosquitoes abundance between years.

Data were analysed using R language version 3.5.0, on an intention-to-treat basis. Mosquito-count data were modelled using a generalised linear mixed model using a template model builder under the *glmmTMB* package,[28] with a negative binomial distribution and zero inflation, accounting for random effects for house and pair, and adjusted for village and repeated measures.[29,30] Negative binomial regression was preferred to a standard Poisson distribution given that the variance in mosquito numbers was greater than the mean. Separate analyses were done for each mosquito species by season. Comparisons of proportions of *A gambiae* and *A arabiensis* were done using logistic regression, with house type, season, and year as primary fixed factors, and cluster nested within the study village as a random factor. Environmental measurements and door opening durations were summarised into hourly readings, with adjusted mean nightly differences and 95% CIs compared using a linear mixed-effects model (*lmer:Test)* with a normal distribution, accounting for village identification, rounds, and date. Comparisons of ITN use were made using χ^2 test with Yates correction. Comparisons between light trap and aspirator collections were made using a *z* test of proportions.

	Star homes		Traditional houses	
	Year 1 (n=99)	Year 2 (n=105)	Year 1 (n=106)	Year 2 (n=107)
Number of children*	1 (1–2)	2 (2–3)	2 (1–3)	2 (1–3)
Number of adults†	0 (0–1)	0 (0–1)	0 (0–1)	0 (0–1)
Number of people	2 (2–3)	2 (2–3)	2 (1–4)	2 (0–3)
ITN use by study child	58 (59%) of 99	97 (92%) of 105	78 (74%) of 106	101 (94%) of 107
Type of ITN				
Permanet	2 (3%) of 58	12 (12%) of 97	3 (4%) of 78	23 (23%) of 101
Olyset	56 (97%) of 58	81 (84%) of 97	75 (96%) of 78	75 (74%) of 101
Miranet	..	4 (4%) of 97	..	3 (3%) of 101
Type of roof				
Thatched	0 (0%) of 99	0 (0%) of 105	86 (81%) of 106	75 (74%) of 101
Metal roof	99 (100%) of 99	105 (100%) of 105	20 (19%) of 106	25 (25%) of 101
Type of wall				
Shade nets	99 (100%) of 99	105 (100%) of 105	0 (0%) of 106	0 (0%) of 107
Mud and stick	0 (0%) of 99	0 (0%) of 105	104 (98%) of 106	105 (98%) of 107
Bricks	0 (0%) of 99	0 (0%) of 105	2 (2%) of 106	2 (2%) of 107
Mean open eave area (m^2)	0·15	0·15	0·7 (0·4)	0·7 (0·4)
Windows				
Present	99 (100%) of 99	105 (100%) of 105	43 (41%) of 106	46 (43%) of 107
Absent	0 (0%) of 99	0 (0%) of 105	63 (59%) of 106	61 (57%) of 107
Mean window area (m^2)	..	..	0·2 (0·4)	0·3 (0·4)
Window cover				
Completely open	0 (0%) of 99	0 (0%) of 105	7 (16%) of 43	9 (21%) of 43
Partial covered	0 (0%) of 99	0 (0%) of 105	21 (49%) of 43	21 (49%) of 43
Curtain	99 (100%) of 99	105 (100%) of 105	12 (28%) of 43	10 (23%) of 43
Screened	99 (100%) of 99	105 (100%) of 105	3 (7%) of 43	4 (9%) of 43
Type of door blade				
Open doorway	0 (0%) of 99	0 (0%) of 105	15 (14%) of 106	19 (18%) of 107
Curtain	0 (0%) of 99	0 (0%) of 105	64 (60%) of 106	68 (64%) of 107
Solid	99 (100%) of 99	105 (100%) of 105	26 (25%) of 106	20 (19%) of 107
Screened	0 (0%) of 99	0 (0%) of 105	1 (1%) of 106	0 (0%) of 107
Mean bedroom area (m^2)	10·0	10·0	3·6 (1·6)	3·5 (1·7)
Light trap working at collection	652 (99%) of 660	693 (98%) of 706	648 (98%) of 660	699 (99%) of 706
Children sleeping on ground floor	46 (7%) of 660	15 (2%) of 706	..	..

Data are median (IQR), %, n (%) of N, or mean (SD), unless otherwise stated. ITN=insecticide-treated net. *Study child represents anyone in the room younger than 13 years. †Adults represent anyone in the room older than 13 years.

Table 1: **Characteristics of trapping rooms**

Role of the funding source

The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report.

	Trap nights	Total caught	Unadjusted mean (95% CI)	Predicted mean (95% CI)	Adjusted RR (95% CI)	Protection (%)	p value
January to December, 2022 (year 1 evaluation)							
Anopheles gambiae							
Traditional houses	660	526	0·80 (0·60–1·03)	0·23 (0·14–0·38)	1		
Star homes	660	208	0·32 (0·20–0·44)	0·09 (0·05–0·17)	0·42 (0·27–0·67)	58%	<0·0001
*Anopheles funestus**							
Traditional houses	660	39	0·06 (0·02–1·01)	0·55 (0·06–4·85)	1		
Star homes	660	5	0·01 (0–0·02)	0·01 (0–0·02)	0·01 (0–0·08)	>99%	<0·0001
Culex species							
Traditional houses	660	3365	5·10 (4·30–5·90)	3·28 (2·58–4·16)	1		
Star homes	660	725	1·10 (0·80–1·13)	1·04 (0·77–1·41)	0·32 (0·25–0·40)	68%	<0·0001
January to December, 2023 (year 2 evaluation)							
Anopheles gambiae							
Traditional houses	706	651	0·86 (0·70–1·02)	0·13 (0·08–0·21)	1		
Star homes	706	514	0·53 (0·36–0·70)	0·06 (0·04–0·11)	0·51 (0·37–0·69)	49%	<0·0001
*Anopheles funestus**							
Traditional houses	706	9	0·01 (0–0·02)	..	..	..	..
Star homes	706	16	0·02 (0–0·04)	..	..	..	..
Culex species							
Traditional houses	706	2191	3·10 (2·31–3·89)	0·96 (0·63–1·44)	1		
Star homes	706	1041	1·48 (1·07–1·87)	0·52 (0·33–0·82)	0·54 (0·40–0·74)	46%	<0·001
January, 2022, to December, 2023 (year 1 + 2 evaluation)							
Anopheles gambiae							
Traditional houses	1366	1177	0·86 (0·70–1·02)	0·17 (0·12–0·25)	1		
Star homes	1366	722	0·53 (0·36–0·7)	0·08 (0·05–0·13)	0·49 (0·35–0·69)	51%	<0·0001
*Anopheles funestus**							
Traditional houses	1366	48	0·04 (0·02–0·06)	..	..	..	..
Star homes	1366	21	0·02 (0·01–0·03)	..	..	..	..
Culex species							
Traditional houses	1366	5556	4·07 (3·51–4·63)	1·93 (1·49–2·50)	1		
Star homes	1366	1766	1·29 (1·05–1·54)	0·76 (0·56–1·03)	0·39 (0·32–0·48)	61%	<0·0001

RR=rate ratio. *Model was not fitted for *Anopheles funestus* given that low numbers were caught.

Table 2: **Indoor mosquito densities in study houses at different times of the year**

	Number of collections	Number of caught by light traps during night	Number of caught by aspirators following morning	Percentage of mosquitoes caught by light trap	p value
Anopheles gambiae					
Traditional houses	220	272	0	272 (100%) of 272	<0·0001
Star homes	220	172	6	172 (96%) of 178	<0·0001
Anopheles funestus					
Traditional houses	220	10	4	10 (71%) of 14	0·13
Star homes	220	22	0	22 (100%) of 22	<0·0001
***Culex* species**					
Traditional houses	220	1310	168	1310 (89%) of 1478	<0·0001
Star homes	220	823	143	823 (85%) of 966	<0·0001

Table 3: **Comparisons between indoor light trap and aspirator collections**

Results

Over the 2-year study period (2022–23), surveys were done to characterise the rooms in which light traps were used (table 1). In 2022 (year 1), fewer children resided in star homes, although the total number of occupants per room remained consistent across both study years. ITN use increased from 136 (66%) of 205 study children's beds in year 1 to 198 (93%) of 212 in year 2 across both house types. House improvement, a common practice in sub-Saharan Africa, was observed during the study. The proportion of traditional houses with metal roofs rose from 20 (19%) of 106 houses to 25 (25%) of 101 houses and mosquito screens on windows from three (7%) of 43 houses to four (10%) of 44 houses between the two surveys. ITN use was lower in year 1 than year 2 in rooms in which light traps were used in star homes (χ^2 30·06; p<0·00001) and traditional houses (χ^2 15·67; p=0·00008). There were proportionally fewer ITNs in star homes than traditional houses in year 1 (χ^2 4·51; p=0·03375), but no difference between groups in year 2 (χ^2 0·098; p=0·75).

Light traps were operational in 2692 (98·5%) of 2732 trapping occasions (table 2), capturing 9290 mosquitoes on 2692 trapping occasions. Of these, 2509 (27·0%) were collected in star homes and 6781 (73·0%) in traditional houses. Most specimens collected were *Culex* species (7322 [78·8%] of 9290), predominantly *Culex quinquefasciatus*, followed by 1899 (20·4%) *A gambiae* and 69 (0·7%) *A funestus* (appendix p 2).

There was no difference in the proportion of *A gambiae* relative to *A arabiensis* between study groups (odds ratio [OR] 1·28, 95% CI 0·93–1·79; p=0·125), although *A gambiae* was more common in the rainy season (December to May) than in the dry season (OR 10·0, 6·7–12·5; p <0·0001), with no difference between year 1 and year 2 (OR 1·4, 0·95–2·08; p=0·090). Because of the low numbers, ORs for *A funestus* could not be reliably modelled.

Mosquito abundance remained low throughout the study, with an average of 0·53 (95% CI 0·36–0·70) *A gambiae* per house per night in star homes, and 0·86 (0·70–1·02) in traditional houses (table 2). *A gambiae* was found on 190 (14%) of 1366 trapping occasions in star homes and 342 (25%) of 1366 in traditional houses. Numbers of *A funestus* captured were also low and were found on 27 (2%) of 1366 occasions in star homes and 55 (4%) of 1366 in traditional houses.

Overall, fewer mosquitoes were captured in star homes than in traditional houses in both years. In adjusted analyses, star homes had 51% less *A gambiae* and 61% less *Culex* species compared with traditional houses. The protective efficacy of star homes against *A funestus* was not calculated because of the low capture numbers, although more were collected in traditional houses (table 3).

Rainfall was higher in year 2 (2452 mm) than year 1 (1410 mm). Although rainfall occurred from January to April in both years, in year 2 there was more rain later in the year (figure 4). Highest numbers of *A gambiae* occurred in February and March and then declined to low levels through the rest of the year. Numbers of *Culex* spp fluctuated widely though the year without a clear pattern. Despite finding appreciable numbers of *A funestus* in the study area before year 1 (data not shown), they were rare during the surveillance period.

440 comparisons were made between light trap collections and aspirator catches (table 3). Light traps consistently captured more mosquitoes than morning aspirator collections. Notably, 172 (96%) of *A gambiae* in star homes and 272 (100%) in traditional houses were caught using light traps.

16 malaria vectors tested positive for *P falciparum* sporozoites, all from the *A gambiae* complex. Sporozoite rates were similar in both star homes and traditional houses (seven [1·3%] of 536 in star homes; nine [1·2%] of 723 in traditional houses; OR 1·00, 95% CI 0·36–2·81; p=0·953). Calculation of entomological inoculation rates were not done since the study groups differed only by the abundance of indoor *A gambiae*, which is described earlier.

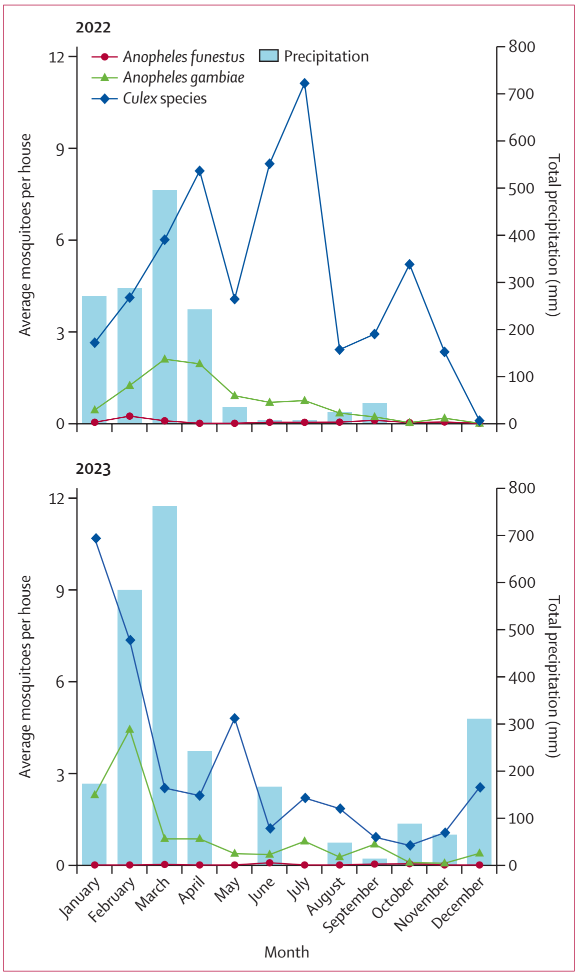

Figure 4: **Seasonality of mosquitoes in relation to rainfall**

Outdoor and indoor temperatures dropped progressively through the night, from a maximum at 1800 h to a minimum at 0600 h (figure 5). Indoor nighttime temperatures were on average 1·5°C warmer than outdoor temperatures in both star homes and traditional houses. At night, star homes were 0·5°C cooler (95% CI 0·2 to 0·9; p=0·010) than traditional houses. Star homes cooled faster than traditional houses between 2100 h and 0000 h, with a mean adjusted difference of –0·4°C (95% CI –0·8 to –0·03; p=0·030). By dawn, star homes were cooler by –1·0°C than traditional houses (–1·4 to –0·7; p=0·0010; appendix p 3). Given that relative humidity is strongly and inversely correlated with temperature, we limit the description to the effects of building typologies on temperature alone, with values of relative humidity included in (table 4) for completeness.

CO_2 concentrations increased indoors and outdoors from 1800 h until 0600 h the following day (figure 6). Overall, there was no difference in the night-time CO_2 concentration between star homes and traditional

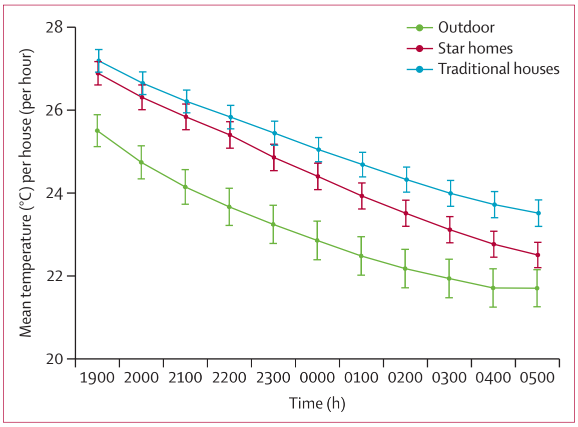

Figure 5: **Unadjusted mean hourly temperature in study houses and outdoors**
Error bars are 95% CIs.

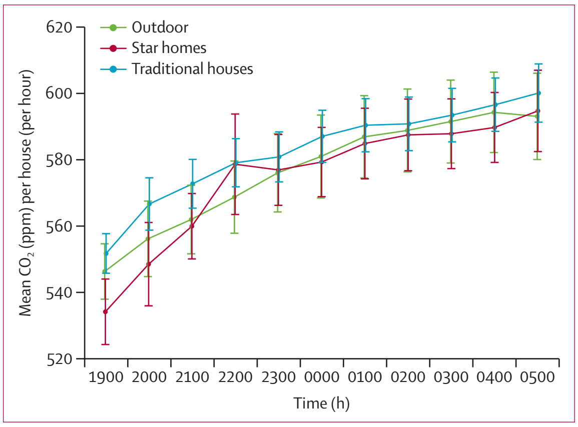

Figure 6: **Unadjusted mean hourly CO_2 concentrations in study houses and outdoors**
Error bars are 95% CIs. ppm=parts per million.

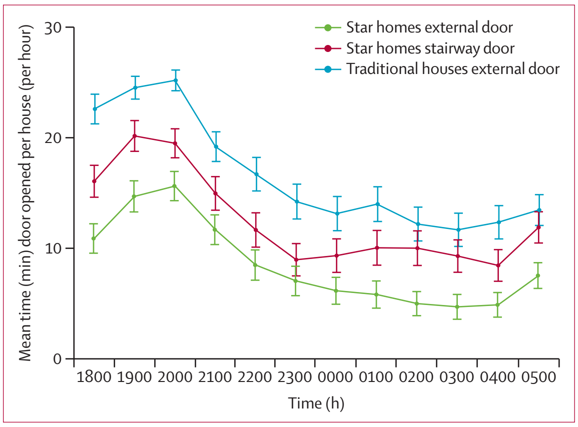

Figure 7: **Unadjusted mean duration of door opening**
Error bars are 95% CIs.

houses (mean difference of –7 parts per million, 95% CI –19 to 6; p=0·285; table 4). Lower CO_2 concentrations, however, were recorded in star homes between 19:00 and 20:00 (adjusted mean difference –17 ppm, 95% CI –29 to –6; p=0·010; appendix p 3). There were no differences in CO_2 concentrations in the wet season (mean 580 ppm, 95% CI 555 to 606), compared with the dry season (mean 571 ppm, 546 to 595, with an adjusted mean difference of 10 ppm, –15 to 34; p>0·151; table 6).

In the evening, door opening increased from 1800 h to 2000 h, then progressively declined before rising after 0400 h. During night-time external doors opened for 53% less time in star homes than traditional houses (7·5 min per hour *vs* 16·2 min per hour; p<0·0001; table 5).

Discussion

This study represents, to our knowledge, the first RCT evaluating the efficacy of an entirely novel house design in reducing malaria transmission in sub-Saharan Africa. Conducted in an area with moderate malaria transmission and increasing use of ITNs, the new screened house design achieved a 51% reduction in *A gambiae* indoors compared with traditional houses over a 2-year period. Although *A funestus* initially showed high abundance, their numbers dropped to very low levels following ITN deployment, making direct comparisons between house types unreliable. Although we had too few *A funestus* to demonstrate that star homes were protective against this complex, the fact that we had a similar proportion of *A arabiensis* and *A gambiae* in both study groups suggests that star homes protect equally well against both species.

Notably, *Culex* species, particularly *Culex quinquefasciatus*, the main vector for lymphatic filariasis[20] in southeast Tanzania and a major nuisance biter, were reduced by 61% in the new house design. Similar reductions in malaria mosquito entry have been documented in other trials involving closed eaves and screened doors and windows in Ethiopia,[31] Malawi,[32] The Gambia,[33] and Côte d'Ivoire.[34] Variability in outcomes across studies, however, such as an absence of protection of screening in one Gambian trial,[35] highlights the importance of local context, intensity of malaria transmission, additional malaria control interventions, intervention design, and quality of screening materials.

Several factors probably contribute to the effectiveness of star homes in limiting mosquito entry. First, the impermeable walls and solid doors of star homes provide a robust barrier against mosquitoes. Second, the self-closing metal doors further enhance protection by minimising the time doors remain open, although this protection can be compromised by evening outdoor activities such as cooking and socialising, which can lead to doors being kept open. Third, the elevated design of the bedrooms in star homes might decrease *Anopheles* mosquito entry, because fewer mosquitoes are found at higher altitudes, although this protective effect might be reduced by walls on lower levels.[22] Fourth, star homes feature smaller eave gaps compared with traditional houses, reducing a major entry route for mosquitoes.

The observed greater reduction in *Culex* species compared with *A gambiae* in star homes can be attributed to two factors. First, the external toilets built close to star homes had a flap of the drop hole designed to prevent mosquitoes from laying eggs in water in the latrine pits, thereby reducing *Culex* mosquito populations, which are often produced in high numbers from latrines.[36] Second, the highly adapted behaviour of *A gambiae* for house entry[37] might make them less susceptible to the barriers than *Culex* mosquitoes. A notable finding was the substantial reduction in *A funestus* following ITN deployment, which has been documented in other studies in the region.[38,39]

Concern about the low number of malaria vectors caught in light traps made us check the catching efficiency of this sampling tool in case we were missing a substantial proportion of those entering houses. Overall, light traps were highly effective at capturing indoor mosquitoes in comparison to resting collections, collecting more than 99% of *A gambiae*. Nonetheless, at least for traditional houses, this value is likely to be overestimated given that a proportion of mosquitoes will have left the room through the open eaves during the night. Findings from experimental huts in east Africa suggest that this overestimation could be as high as 51%, with 85% leaving through open windows and doors and 15% through eave gaps.[40]

The sporozoite rates over the 2-year study were low and similar between study groups. This result was anticipated given that considerable mixing of the population occurs within mosquito populations in a village.

The disparity between the high protective efficacy (77–96%) reported in the pilot study[12] and the 51% reduction observed in this RCT could be due to several factors. First, the pilot study's use of outdoor mosquito collections probably inflated protective efficacy estimates. Second, the pilot study collected mosquitoes during one rainy season when mosquito numbers were considerably higher than the present study area collecting an average of 12.6 *A gambiae* mosquitoes captured per night in Muheza.[41] People are more likely to keep their doors shut at night when mosquito biting abundance is high, compared with when they are low. Other studies have demonstrated increased use of mosquito nets[42] and mosquito repellents[43] as mosquito numbers increase.

Star homes were notably cooler at night compared to traditional houses, a result of their low thermal mass construction materials of metal roofs and shade cloth walls compared with the high thermal mass materials used for traditional houses which includes thatched roofs and mud walls. The cooler temperatures in elevated bedrooms[44] might encourage greater use of bednets, potentially reducing malaria risk. CO_2 concentrations gradually increased through the night. This increase is largely a result of respiration from plants, taking in oxygen and producing CO_2,[45] and from the soil,[46] with CO_2 produced from plant roots, the rhizosphere, microbes, and fauna. By contrast, CO_2 produced by people sleeping indoors has a markedly different pattern, rising rapidly after the bedroom is occupied and then declining slightly through the night.[15] CO_2 concentrations between house types were similar, except for lower concentrations in star homes during the early evening. Overall, our results suggest that traditional houses with large open eaves were similarly well ventilated as the star

	n	Unadjusted mean (95% CI)	Adjusted mean difference (95% CI)	p value
Dry season (June to November), 2022–23				
Temperature (°C)				
Traditional houses	120	24·4 (23·1 to 25·8)	1	
Star homes	120	24 (22·6 to 25·3)	–0·46 (–0·87 to –0·02)	0·03
Outdoors	52	22·4 (21·1 to 23·6)	NA	NA
Relative humidity (%)				
Traditional houses	120	76 (75 to 78)	1	
Star homes	120	77 (75 to 79)	0·5 (–1·3 to 2·4)	0·557
Outdoors	52	85 (82 to 87)	NA	NA
Carbon dioxide (ppm)				
Traditional houses	120	570 (547 to 593)	1	
Star homes	120	574 (551 to 598)	4·64 (–7·46 to 17·43)	0·449
Outdoors	52	561 (533 to 588)	NA	NA
Wet season (December to May), 2022–23				
Temperature (°C)				
Traditional houses	87	26·3 (24·9 to 27·6)	1	
Star homes	87	25·8 (24·4 to 27·1)	–0·52 (–0·93 to –0·09)	0·019
Outdoors	40	24·8 (23·1 to 26·6)	NA	NA
Relative humidity (%)				
Traditional houses	87	79 (74 to 83)	1	
Star homes	87	79 (75 to 84)	0·82 to (–1·04 to 2·68)	0·385
Outdoors	40	81 (72 to 91)	NA	NA
Carbon dioxide (ppm)				
Traditional houses	87	582 (541 to 621)	1	
Star homes	87	567 (526 to 607)	–14·39 (–35·56 to 6·73)	0·185
Outdoors	40	577 (519 to 626)	NA	NA
Dry and wet seasons (January, 2022, to December, 2023)				
Temperature (°C)				
Traditional houses	207	25·2 (24 to 26·3)	1	
Star homes	207	24·7 (23·6 to 25·9)	–0·46 (–0·80 to –0·10)	0·010
Outdoors	92	23·6 (22·2 to 25)	NA	NA
Relative humidity (%)				
Traditional houses	207	78 (75 to 81)	1	
Star homes	207	78 (76 to 81)	0·24 (–1·31 to 1·73)	0·752
Outdoors	92	83 (78 to 88)	NA	NA
Carbon dioxide (ppm)				
Traditional houses	207	578 (555 to 601)	1	
Star homes	207	571 (548 to 594)	–6·67 (–18·79 to 5·68)	0·285
Outdoors	92	573 (540 to 603)	NA	NA

Adjusted mean difference values were adjusted for village identification and rounds. NA=not applicable. ppm=parts per million.

Table 4: **Environmental measurements**

Variable	Description	Number of houses	Mean min/h (95% CI)	Adjusted mean difference (95% CI)	p value
Dry season (June to November)					
Traditional houses	Main door	88	17·7 (14·5 to 21)	1	Ref
Star homes	Stairway door	88	11·4 (7·9 to 14·9)	–5·9 (–10·2 to –1·5)	0·011
Star homes	Main door	88	6 (2·5 to 9·5)	–11·3 (–15·7 to –6·1)	<0·00001
Wet season (December to May)					
Traditional houses	Main door	72	17·7 (14·5 to 20·9)	1	Ref
Star homes	Stairway door	72	11·8 (8·5 to 15·2)	–3·8 (–8·4 to 0·7)	0·256
Star homes	Main door	72	6·4 (3 to 9·7)	–5·4 (–9·9 to –0·9)	0·025
Dry and wet seasons (January, 2022, to December, 2023)					
Traditional houses	Main door	160	16·2 (13·5 to 18·9)	1	Ref
Star homes	Stairway door	160	11·6 (8·7 to 14·3)	–4·6 (–8·1 to –1·2)	0·012
Star homes	Main door	160	7·5 (4·8 to 10·3)	–8·7 (–12·1, –5·2)	<0·00001

Mean values were adjusted for house type, rounds and month of collections.

Table 5: Duration of door opening

homes. This result is supported by our work in The Gambia showing houses with open eaves are well ventilated compared with those with closed eaves,[47] which are common in more modern rural housing in sub-Saharan Africa.

Self-closing doors in star homes were open less frequently than in traditional houses, with door-opening peaking during early evening hours when people are busy and mosquito biting activity is rising.[37] The prolonged opening of internal stairway doors provided additional access for mosquitoes to bedrooms. The findings suggest that door-closing behaviour is crucial for effective mosquito control and that improvements are needed to enhance the design of star homes and improve health messaging on encouraging people to keep their doors closed at night.

Study limitations include, first, the inability to mask participants, common in environmental interventions. Second, potential underestimation of protective efficacy because the light traps' visibility in star homes from outside the house might have artificially increased mosquito collections,[20] and the large open eaves in traditional houses allowing a proportion of mosquitoes to escape from the room at night. Cost considerations for constructing a star home were not presented here but the economics of star homes and their environmental effects will be described in a future paper.

This study demonstrates that the novel star home design, featuring integrated mosquito screening, effectively reduces the entry of mosquitoes in sub-Saharan Africa. These findings add to the growing evidence supporting house screening as a valuable supplementary strategy for the control of malaria and lymphatic filariasis and is supported by WHO's Global Vector Control Response 2017–30.[48] Although mosquito screening has traditionally been applied retrospectively, the anticipated construction of millions of new homes across the continent in the next 25 years presents a unique opportunity to incorporate mosquito screening into the initial design of these structures, thereby enhancing malaria prevention efforts.

Contributors

LvS, JK, and SWL conceived and designed the overall study. ASM, SWL, and FOO designed the entomological and environmental surveillance. JK designed the star home. ASM and AJN collected light-trap survey data together with the field assistants. ASM and AJN did the data entry, supervised by SWL and FOO. SM, TCB and JK assisted in the study design and enrolment of study houses and other logistics in the field. TCB helped advise on the environmental measurements.
ASM and HSN verified the underlying data under the supervision of FOO and SWL. JB and HSN supervised and confirmed the statistical analyses done by ASM. ASM, SWL, and FOO wrote the first draft of the manuscript. All authors read and approved the final manuscript.
SWL had final responsibility for submitting the manuscript for publication.

Declaration of interests

We declare no competing interests.

Data sharing

De-identified data are available to researchers whose proposed purpose of use is approved by the Mahidol Tropical Medicine Research Unit of the University of Oxford. Related documents such as the study protocol and the informed consent form will be made available on request.
To request the dataset, please send a signed data request form to datasharing@tropmedres.ac. The data request form can be found online at https://www.tropmedres.ac/files/moru-bangkok-files/2-dataapplicationformv3-16nov2018.docx/view.

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