

Affordable house designs to improve health in rural Africa: a field study from northeastern Tanzania

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Summary

Background The population of sub-Saharan Africa is currently estimated to be 1245 million and is expected to quadruple by the end of the century, necessitating the building of millions of homes. Malaria remains a substantial problem in this region and efforts to minimise transmission should be considered in future house planning. We studied how building elements, which have been successfully employed in southeast Asia to prevent mosquitos from entering and cooling the house, could be integrated in a more sustainable house design in rural northeastern Tanzania, Africa, to decrease mosquito density and regulate indoor climate.

Methods In this field study, six prototype houses of southeast Asian design were built in the village of Magoda in Muheza District, Tanga Region, Tanzania, and compared with modified and unmodified, traditional, sub-Saharan African houses. Prototype houses were built with walls made of lightweight permeable materials (bamboo, shade net, or timber) with bedrooms elevated from the ground and with screened windows. Modified and unmodified traditional African houses, wattle-daub or mud-block constructions, built on the ground with poor ventilation served as controls. In the modified houses, major structural problems such as leaking roofs were repaired, windows screened, open eaves blocked with bricks and mortar, cement floors repaired or constructed, and rain gutters and a tank for water storage added. Prototype houses were randomly allocated to village households through a free, fair, and transparent lottery. The lottery tickets were deposited in a bucket made of transparent plastic. Each participant could draw one ticket. Hourly measurements of indoor temperature and humidity were recorded in all study houses with data loggers and mosquitoes were collected indoors and outdoors using Furvela tent traps and were identified with standard taxonomic keys. Mosquitoes of the *Anopheles gambiae* complex were identified to species using PCR. Attitudes towards the new house design were assessed 6–9 months after the residents moved into their new or modified homes through 15 in-depth interviews with household heads of the new houses and five focus group discussions including neighbours of each group of prototype housing.

Findings Between July, 2014, and July, 2015, six prototype houses were constructed; one single and one double storey building with each of the following claddings: bamboo, shade net, and timber. The overall reduction of all mosquitoes caught was highest in the double-storey buildings (96%; 95% CI 92–98) followed closely by the reduction found in single-storey buildings (77%; 72–82) and lowest in the modified reference houses (43%; 36–50) and unmodified reference houses (23%; 18–29). The indoor temperature in the new design houses was 2.3°C (95% CI 2.2–2.4) cooler than in the reference houses. While both single and two-storey buildings provided a cooler indoor climate than did traditional housing, two-storey buildings provided the biggest reduction in mosquito densities (96%, 95% CI 89–100). Seven people who moved into the prototype houses and seven of their neighbours (three of whom had their houses modified) participated in in-depth interviews. After living in their new prototype houses for 6–9 months, residents expressed satisfaction with the new design, especially the second-storey sleeping area because of the privacy and security of upstairs bedrooms.

Interpretation The new design houses had fewer mosquitoes and were cooler than modified and unmodified traditional homes. New house designs are an underused intervention and hold promise to reduce malaria transmission in sub-Saharan Africa and keep areas malaria-free after elimination.

Funding Ruth W Jensens Foundation, Copenhagen and Hanako Foundation, Singapore.

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Introduction

The population of sub-Saharan Africa is growing at an unprecedented rate and is likely to increase from 1.2 billion in 2015, to 4.4 billion by the end of the century.¹ This increasing population will necessitate the building of millions of houses across the region. Because between 80% and 100% of malaria transmission occurs

indoors at night,² there is an unprecedented opportunity to design homes that keep malaria vectors out. A growing body of work shows that improved housing reduces malaria transmission.³

People's main complaint about using insecticide-treated bednets is that they feel uncomfortably hot.⁴ When designing houses that reduce mosquito entry it is

Lancet Planet Health 2017;
1: e188–99

This online publication has been corrected. The corrected version first appeared at thelancet.com/planetary-health on Sept 7, 2017

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Research in context

Evidence before this study

We searched PubMed between Jan 1, 2010, and July 21, 2017, with the terms “housing”, combined with “Africa”, “health”, and/or “malaria” with no date restrictions for published English-language reports. We found two large reviews have assessed the evidence for housing improvements (other than bednets) to reduce malaria in sub-Saharan Africa. The first was a systematic review and meta-analysis of 90 studies published between 1900 and 2013. Residents of modern houses had 47% lower odds of malaria infection than did those of traditional houses and a 45–65% lower odds of clinical malaria. Traditional homes were deemed as those having mud walls, thatched roofs, earth floors, open eaves, no ceiling, and no screening. Improved homes had full or ceiling screening, finished walls and floors, corrugate iron roofs, and closed eaves. A more recent multi-country analysis of 15 demographic and health surveys and 14 Malaria Indicator Surveys done in 21 countries across sub-Saharan Africa confirmed that housing quality is an important risk factor for malaria infection across the spectrum of malaria endemicity. Importantly, this analysis noted that the protection afforded by improved housing quality against malaria was similar to the protection afforded by impregnated bednets.

Added value of this study

Our findings showed that a southeast Asian house design (with elevated structure, screened windows, and permeable walls to maximise cross-ventilation), especially those with two floors, reduced mosquito densities in homes compared with traditional sub-Saharan African homes (made with wattle-daub

or mud-block construction, built on the ground with poor ventilation), that indoor temperatures were lower in houses adapted to tropical conditions than in traditional homes, and that residents’ and neighbours’ opinions were positive of the prototype houses. The findings show that is accepted by villagers in rural Tanzania to live in double storey buildings. Living in such buildings is more comfortable due to lower temperatures and reduced mosquito densities.

Implications of all the available evidence

Findings of observational studies have shown a strong association between house improvements (including metal roofs, closed eaves, eaves tubes, insecticide-treated curtains, and screened windows and doors) and reduced malaria transmission. However, such incremental improvements do not address the fundamental problems of the traditional rural African house design, namely poorly ventilated structures built on ground level. Elevating buildings insulates the living space from heat radiating from the ground and improves airflow, essential for a healthy air quality and a comfortable indoor environment, particularly in hot, humid climates. Our findings suggest it might be possible to decrease malaria transmission and improve comfort through changes in house design in hot humid climate zones in sub-Saharan Africa. Furthermore, improved ventilation might facilitate the use of bednets and reduce the transmission of respiratory tract infections. Added water harvesting and latrines might reduce the risk of enteric infections. Large randomised clinical trials are now needed to assess the clinical benefits and cost-effectiveness of modified house designs on malaria transmission and respiratory tract and enteric infections.

therefore important to keep the house cool. The climate “comfort zone” is a term used by physiologists and architects to describe the optimum combinations of temperature, humidity, and airflow that people find agreeable.^{5,6} Of these variables, airflow is of crucial importance but is often overlooked. In extremely hot and humid conditions even a small attenuation of airflow is sufficient to render a space uncomfortable, if not unbearable. Because airflow is reduced by about 60% in a space enclosed by a bednet,⁷ it is unsurprising that in tropical Africa insecticide-treated bednets are inconsistently used.⁴

The traditional sub-Saharan mud hut is a wattle-daub (adobe) or mud-block construction, built on the ground with poor ventilation.⁸ By contrast, traditional rural homes in southeast Asia tend to be well adapted to the hot, humid climate.⁸ Houses are elevated on stilts and permeable materials such as bamboo slats are used for the construction of walls. Elevating the structure and using permeable walls promotes airflow, reduces the indoor temperature, and optimises the overall indoor climate. It is also likely that raising the house above ground level reduces the entry of *Anopheles gambiae* mosquitoes,⁹ the major African

malaria vector, because most mosquitos fly no more than 1 m above the ground.¹⁰

Computational fluid dynamics modelling developed to predict indoor climate in contemporary urban structures within industrialised countries can be applied to rural housing in low-income countries.¹¹ Such models predict improved indoor climate by elevating living spaces sufficiently to allow airflow under the house. Constructing houses with air-permeable building materials such as shade nets (a plastic fabric used primarily in agriculture to prevent excessive sun and rain exposure), loosely spaced timber planks or bamboo cladding and large, preferably screened, windows will facilitate airflow and cool the interior.⁸

The design of residential buildings can have several health benefits (figure 1). For example, improved airflow and a lower indoor temperature make it more comfortable to sleep under a bednet, which could increase bednet use in malaria-endemic countries. Elevating homes can reduce indoor-mosquito densities^{12,13} and thus the risk of mosquito-borne diseases. Laying a floor compared with compacted earth reduces exposure to soil transmitted helminths. Separating wood burning stoves from living and sleeping spaces reduces indoor air pollution and

hence the risk of respiratory illness and coronary heart disease.^{14–16} Separated kitchens with a fireplace and a chimney also reduce the risk of starting an accidental fire. Including rain collection gutters on the roofs and water storage tanks can provide a safe water supply.¹⁷ Finally, providing well designed latrines improves sanitation and in combination with a safe water supply reduces the enteric disease burden.¹⁸

In rural Africa, several interventions have been used to modify individual aspects of the home such as the closing of eaves,¹⁹ adding eaves tubes,^{20,21} installing insecticide-treated curtains,²² screening windows and doors,²³ or replacing thatched roofs with corrugate iron.²⁴ Although such modifications can provide incremental improvements, they cannot overcome the fundamental design flaws of traditional, rural African homes, particularly poor heat insulation and restricted airflow. This study explored how building elements, which have been employed in southeast Asia, could be integrated in a novel low-cost house design in rural east Africa. As a first step to assess the benefits of such a new house design, we compared mosquito density, indoor climate, and acceptability to the residents across new designs of African houses in rural Tanzania.

Methods

Study site

The study was done in the village of Magoda in Muheza District, Tanga Region, Tanzania. At the time of the 2012 national census, Magoda had a population of 2934 individuals living in 678 households.²⁵ Subsistence farming and informal trade are the major sources of income. The area is endemic for *Plasmodium falciparum* malaria. As in many other parts of sub-Saharan Africa,²⁶ there has been a remarkable decrease in the burden of malaria during the past decade. Cross-sectional surveys in Magoda village showed that the prevalence of *P. falciparum* infections in individuals younger than 20 years decreased from 84% in 1992, to 34% in 2004, and 7% in 2012.²⁷

House construction

The prototype buildings were designed by JBK (Ingvarsten Arkitekt, Copenhagen, Denmark; figure 2). After meetings with village leaders, the construction and study plans were discussed with the entire village; the discussions were led by social science research team members. A free, fair, and transparent lottery was done in which each interested village household had the same chance to win a new prototype house. The same number of lottery tickets as participants in the lottery were prepared. Six of the lottery tickets were marked as winners when opened. The lottery tickets were deposited in a bucket made of transparent plastic. Each participant could draw one ticket. The strength of this form of randomisation is the transparency for the villagers and hence potentially preferable to computer-generated

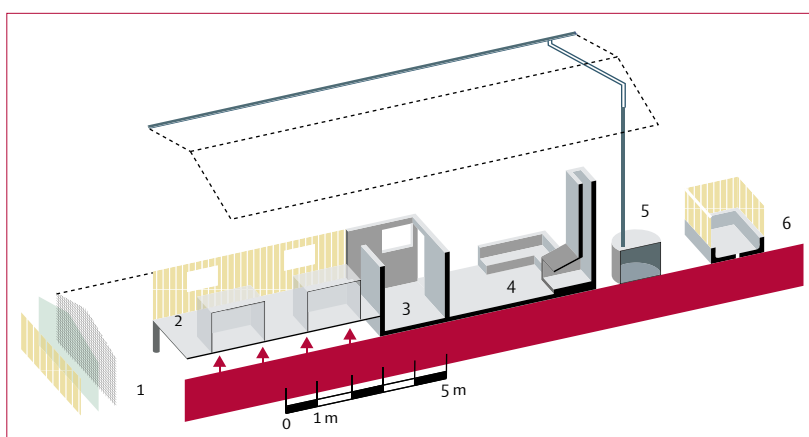


Figure 1: The prototype houses

(1) Porous wall materials (cladding) that are air permeable. (2) A concrete or timber floor that is elevated from the ground for sleeping areas. (3) A reinforced storage area that can be locked. (4) An outdoor cooking area with chimney connected to the main building and covered by a roof. (5) A water harvesting system that allows the collection of rain water through gutters and storage of water in a large plastic container. (6) An outdoor latrine.

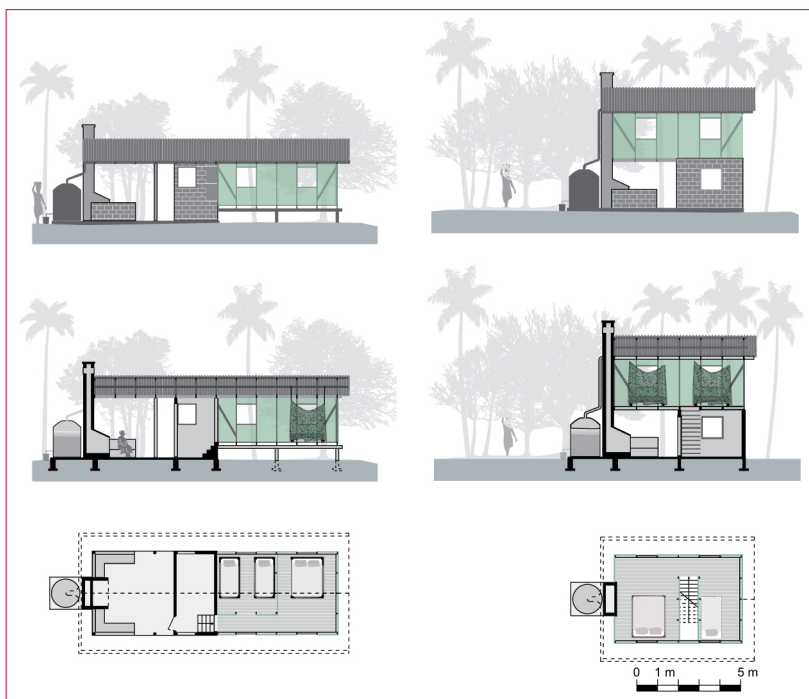


Figure 2: Construction plan drawings (elevation, cross-section, and ground plan) of a single-storey and a double-storey prototype house

random numbers for political reasons. The members of the winning households were asked to help in the construction of a new building in direct vicinity of their existing house. Once the construction was completed, the household members moved into the new building.

Six prototype houses were constructed, which were divided into three groups based on the material used for cladding (figure 3). Group 1 houses used unimpregnated bamboo (*Bambusa vulgaris*), which is a highly popular building material in Asia; Group 2 houses used shade

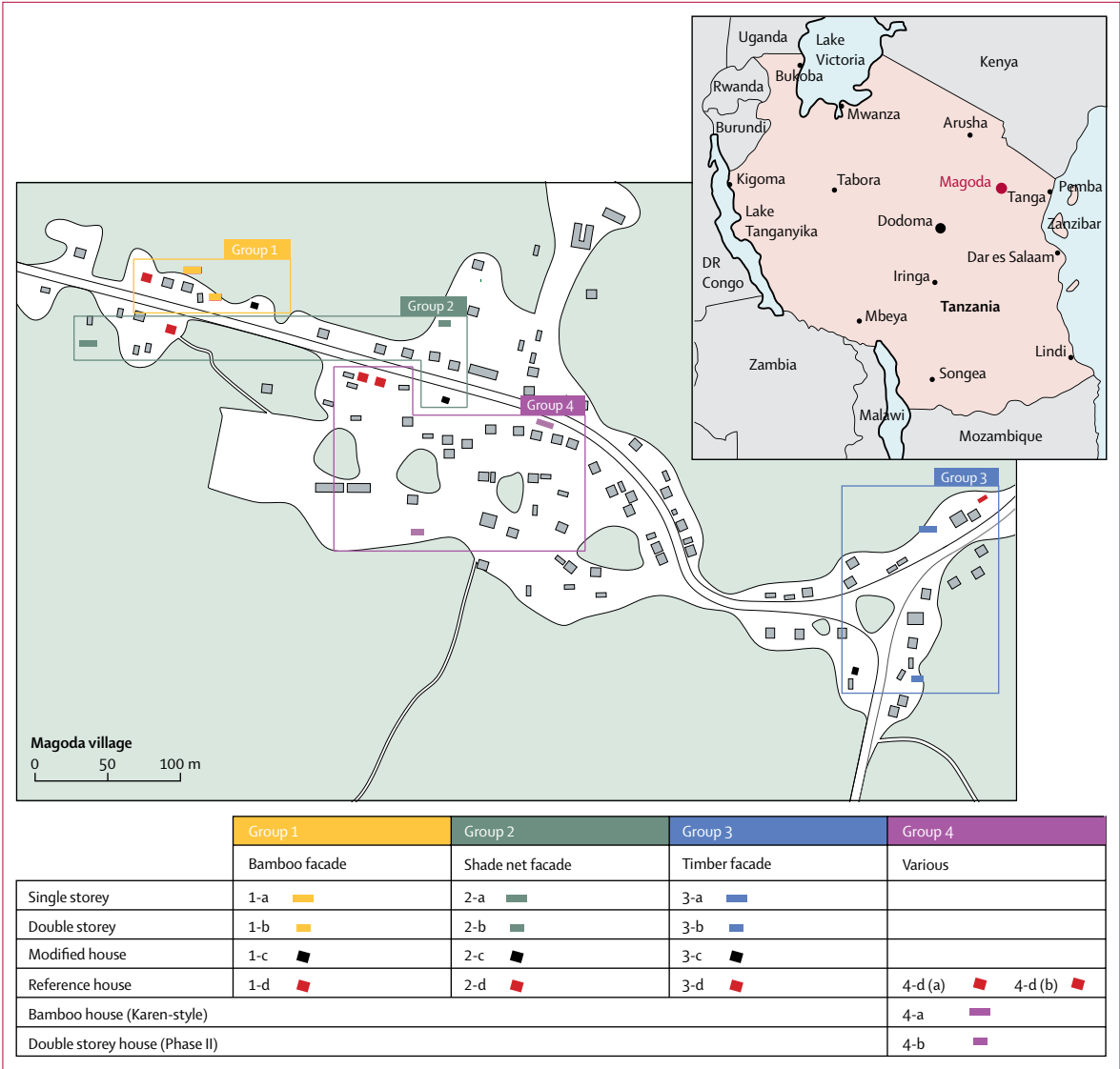


Figure 3: The study area and location of study houses

net as cladding material (High Density Polyethylene Net, UV Stabilised, Multiknit Ltd, South Africa, locally purchased; appendix) and insect netting to screen windows and eaves (High Density Polyethylene Net, UV Stabilised, Multiknit Ltd, South Africa, mesh size 2 mm×6 mm, locally purchased; appendix). Group 3 used cypress timber (*Cupressus lusitanica*), a traditional cladding material (appendix). Each house group included four houses: one single storey prototype building, one double storey prototype building, one traditional house which had been modified and one traditional house which was left unchanged and served as control. In the modified houses, major structural problems such as leaking roofs were repaired, windows screened (insect net, mesh size 2 mm×2 mm, locally purchased), open eaves blocked with bricks and mortar, cement floors

repaired or constructed, rain gutters and a tank for water storage added. Extra windows were installed in bedrooms with only one window to secure cross ventilation. Two new buildings were constructed for reference purposes, did not share the characteristics of the prototype houses, and were included in Group 4. One of the new buildings in Group 4 was a typical Thai-Karen bamboo hut constructed in the village by carpenters from Tak Province, northeastern Thailand. The bamboo used in the construction of the Thai-Karen house was initially impregnated with a crystalline organophosphate insecticide (Chlorpyrifos, 480 g/L, Dow AgroScience, France) before construction and subsequently sprayed with carbaryl-containing and permethrin-containing insecticide (Ultravin, 5%, Ultravetis, Kenya). A double-storey house using bamboo and shade net was built next

See Online for appendix

to the school to provide housing for teachers and inspiration for students.

A video showing the house construction is available online.

Climate data

Hourly measurements of indoor temperature and humidity were recorded in all study houses using HOBO data loggers (ONSET, Bourne, MA, USA). The data loggers were installed in the bedroom used by the household head and were installed 500 mm and 1000 mm above the floor.

Psychrometric testing

The software package LadyBug (LadyBug Products, Athol, ID, USA) was used to estimate the percentage of time occupants of various house types spent in the comfort zone.²⁸ The comfort zone is defined by the comfort polygon for temperature and relative humidity and an estimated percentage of people dissatisfied. The human energy balance model used by the psychrometric chart is the predicted mean vote model developed by P O Fanger.⁵ The predicted mean vote model is a seven-point scale from cold (−3) to hot (+3) that is used in comfort surveys. Each integer value of the scale indicates the following: −3: Cold, −2: Cool, −1: Slightly Cool, 0: Neutral, +1: Slightly Warm, +2: Warm, +3: Hot. The accepted range of comfort is a predicted mean vote between −1 and +1 and defines the area of the comfort polygon on the psychrometric chart.

Entomological assessment

Mosquitos were collected using Fuvrel tent traps²⁹ during the rainy season (February; appendix). Participants agreeing to sleep in the tent traps were men aged 18 years and older who provided a signed informed consent form, abstained from alcohol and smoking, and agreed not to leave the tent from 2200 h to 0600 h, except to use bathroom facilities. Mosquitoes were collected from 2200 h to 0600 h. In the morning, trapped mosquitoes were collected into paper cups covered with netting and killed by placing the cups inside a freezer at −20°C for about 1 h. Mosquitoes were identified using standard taxonomic keys. Mosquitoes of the *Anopheles gambiae* complex were identified to species using PCR.³⁰

Acceptability assessment

Attitudes towards the novel designs and modified traditional housing were assessed 6–9 months after the residents moved into their new or modified homes through 15 in-depth interviews and five focus group discussions. Household heads of the new houses, modified houses and reference houses were interviewed in Swahili, the local language, using pretested interview guides (appendix). Neighbours of each group of prototype housing participated in a focus group discussions. Participants were invited to one of the three focus group

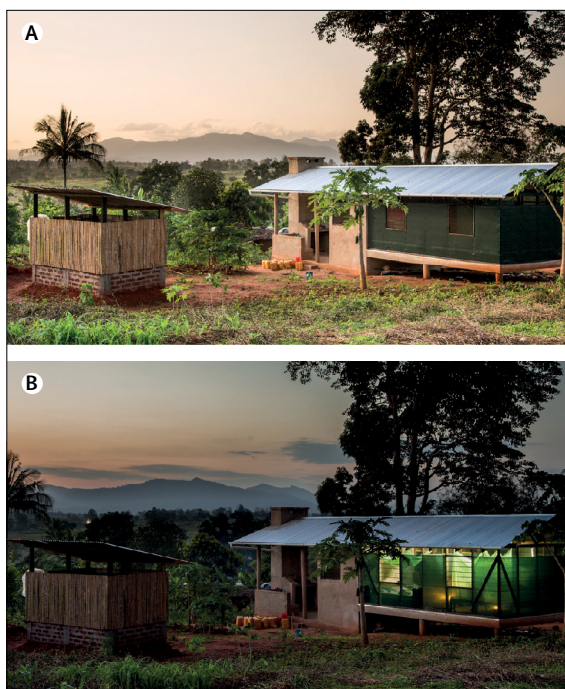


Figure 4: A single-storey, shade-net house at day (A) and evening (B)

discussions according to the neighbouring group of prototype houses (bamboo, shade net, and timber houses). Community members from further afield in the same village or the nearby sub-village also participated in focus group discussions. The respondents who participated in the focus group discussions and in-depth interviews were aged between 35 years and 80 years, with equal proportions of men and women (appendix shows participant characteristics). After receiving training in interview techniques, research assistants did the in-depth interviews and focus group discussions. To minimise the potential for desirability bias, the research assistants were not part of the study implementation team. All in-depth interviews and focus group discussions were digitally recorded, transcribed in Swahili, and then translated into English for analysis.

Before study activities started, written informed consent was obtained from the household head and other volunteers sleeping in tent traps. Verbal informed consent was obtained from the in-depth interview and focus group discussions participants. A Clearance Certificate for Conducting Medical Research in Tanzania was obtained from the National Institute for Medical Research on Aug 14, 2014 (NIMR/HQ/R.8a/Vol. IX/1797), and extended on Jan 14, 2016 (NIMR/HQ/R.8c/Vol. II/555).

Data management and analysis

Climate data were downloaded from each data logger at monthly intervals and transferred into a central database. Data collected around 2130 h give or take 30 min were used for the analysis. The temperature at bedtime,

For the video see <https://vimeo.com/173448910/fd4d31045c>

	Cladding	Number of storeys	m ²	Roof	Floor	Screened	Eaves	Cooking	Water supply	Latrine	Cost (\$USD)
1-a	Bamboo	One	48	Iron	Timber	No screen	Open	Outdoor chimney	Sim tank	Yes	4896
1-b	Bamboo	Two	48	Iron	Timber	No screen	Open	Outdoor chimney	Sim tank	Yes	4774
1-c	Modified	One	51	Iron	Concrete	No screen	Open	Outdoor	Sim tank	Yes	6220
1-d	Reference	One	46	Iron	Soil	No screen	Open	Indoor	None	None	4231
2-a	Shade net	One	48	Iron	Concrete	Screened	Covered by net	Outdoor chimney	Sim tank	Yes	4661
2-b	Shade net	Two	48	Iron	Concrete	Screened	Covered by net	Outdoor chimney	Sim tank	Yes	5775
2-c	Modified	One	44	Iron	Concrete	No screen	Closed	Indoor	Sim tank	Yes	1989
2-d	Reference	One	44	Iron	Soil	No screen	Open	Indoor	None	None	4231
3-a	Timber	One	48	Iron	Timber	No screen	Open	Outdoor chimney	Sim tank	Yes	5775
3-b	Timber	Two	48	Iron	Timber	No screen	Open	Outdoor chimney	Sim tank	Yes	6125
3-c	Modified	One	45	Iron	Concrete	No screen	Closed	Indoor	Sim tank	Yes	6220
3-d	Reference	One	36	Iron	Soil	No screen	Open	Indoor	None	None	4231

Group 1 houses used bamboo for cladding, group 2 houses used shade net, a plastic material, and group 3 used cypress timber. Sim tank=a 2000 L water tank.

Table 1: Characteristics of study houses

Species caught											Total number of mosquitoes caught		Difference between outdoor catch (OC) and indoor catch (IC)	Percent reduction (OC-IC)/ OC*100
Anopheles arabiensis		Anopheles gambiae		Culex quinquefasciatus		Mansonia species		Other Anophelines		In	Out			
In	Out	In	Out	In	Out	In	Out	In	Out					
Group 1 (bamboo)														
1-a	4	20	10	47	8	33	0	21	5	2	27	123	96	78%
1-b	1	14	1	28	3	10	0	10	0	3	5	65	60	92%
1-c	5	18	7	47	6	15	1	10	23	3	42	93	51	55%
1-d	7	10	30	37	5	15	6	9	20	8	68	79	11	14%
Group 2 (shade net)														
2-a	1	11	3	39	1	9	1	16	2	8	8	83	75	90%
2-b	0	3	0	17	0	11	0	21	0	8	0	60	60	100%
2-c	3	7	11	21	6	10	8	19	10	3	38	60	22	37%
2-d	9	15	18	38	6	12	1	12	14	6	48	83	35	42%
Group 3 (timber)														
3-a	4	13	3	6	9	9	2	22	7	7	25	57	32	56%
3-b	0	5	1	22	2	17	0	15	0	9	3	68	65	96%
3-c	8	3	10	16	6	7	0	9	8	9	32	44	12	27%
3-d	6	10	22	18	3	8	4	17	23	12	58	65	7	11%
Total number	48 (14%)	129 (15%)	116 (33%)	336 (38%)	55 (16%)	156 (18%)	23 (6%)	181 (21%)	112 (32%)	78 (9%)	354 (100%)	880 (100%)	526	60%
1-a=bamboo cladding, single storey. 1-b=bamboo cladding, double storey. 1-c=modified house. 1-d=reference unaltered traditional house. 2-a=shade net, single storey. 2-b=shade net, double storey. 2-c=modified house. 2-d=reference unaltered traditional house. 3-a=timber cladding, single storey. 3-b=timber cladding, double storey. 3-c=modified house. 3-d=reference unaltered traditional house.														
Table 2: Number of mosquitoes caught by tent trap indoors and outdoors, by mosquito species and house type														

between 2100 h and 2200 h, was considered most relevant for the decision to use a bednet or not. Mean temperatures with 95% confidence intervals were calculated for each building. Bedtime temperatures were modelled using

the BoxCox Transformation regression model.^{31,32} The predicted bedtime temperatures from the BoxCox Transformation models were smoothed using cubic spline. The cubic splined bedtime values (including

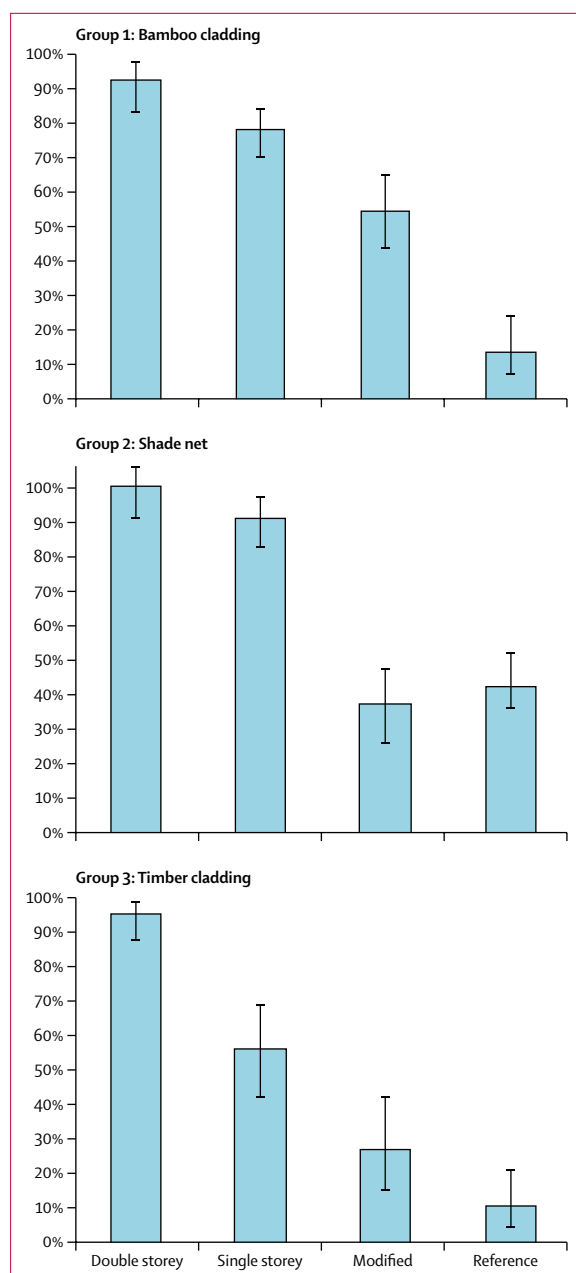


Figure 5: The percentage reduction in mosquitoes caught by tent trap indoors and outdoors by house type

a 95% confidence band) were then plotted over time and found to be skewed. The BoxCox Transformation modelling provides a reasonably appropriate transformation to the data and the cubic splining helps to obtain smooth curves.³³

Entomology data were double entered. The difference in mosquitoes caught indoors and outdoors was calculated for each night and each house. The reduction in total mosquito catches was calculated as $(OC-IC)/OC \times 100$, where OC is outdoor catch, and IC indoor catch. Proportions with 95% confidence intervals were calculated.

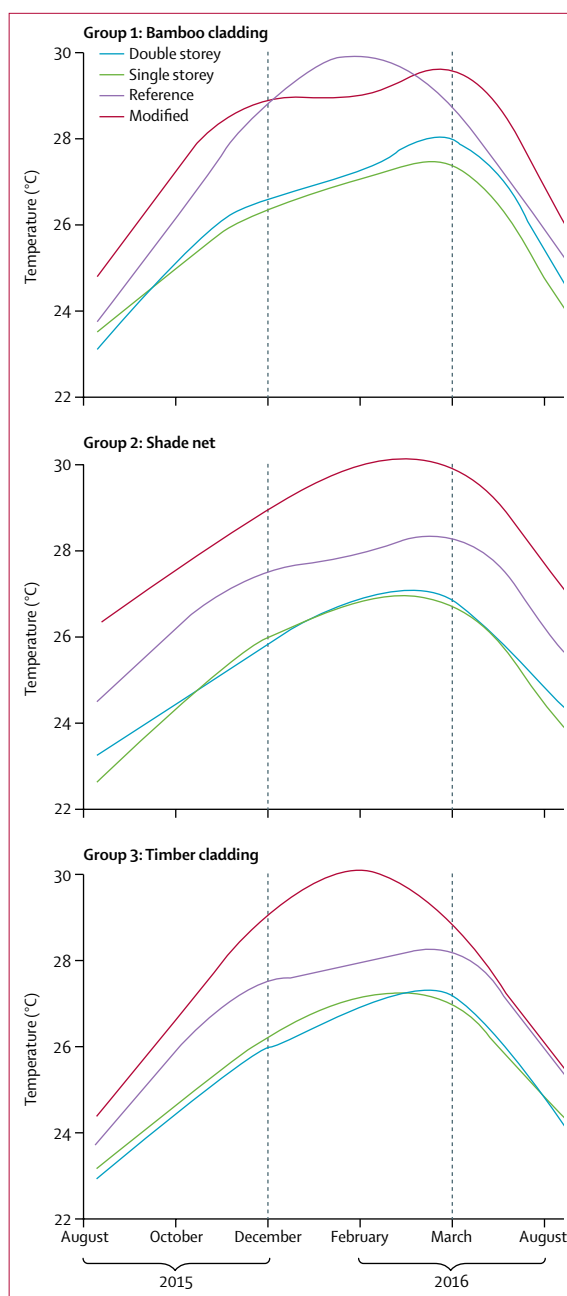


Figure 6: Mean indoor temperature at 2130 h between August, 2015, and July, 2016, by house type

Reference house: a traditional house which was left unchanged and served as control. Modified house: major structural problems such as leaking roofs were repaired, windows screened, open eaves blocked with bricks and mortar, cement floors repaired or constructed, rain gutters and a tank for water storage added. Extra windows were installed in bedrooms with only one window to secure cross ventilation.

The analysis process began by developing codes, which are meaningful segments of texts that are used for condensing and organising qualitative data into smaller units. Initial codes were developed from the main research questions and interview guides. These

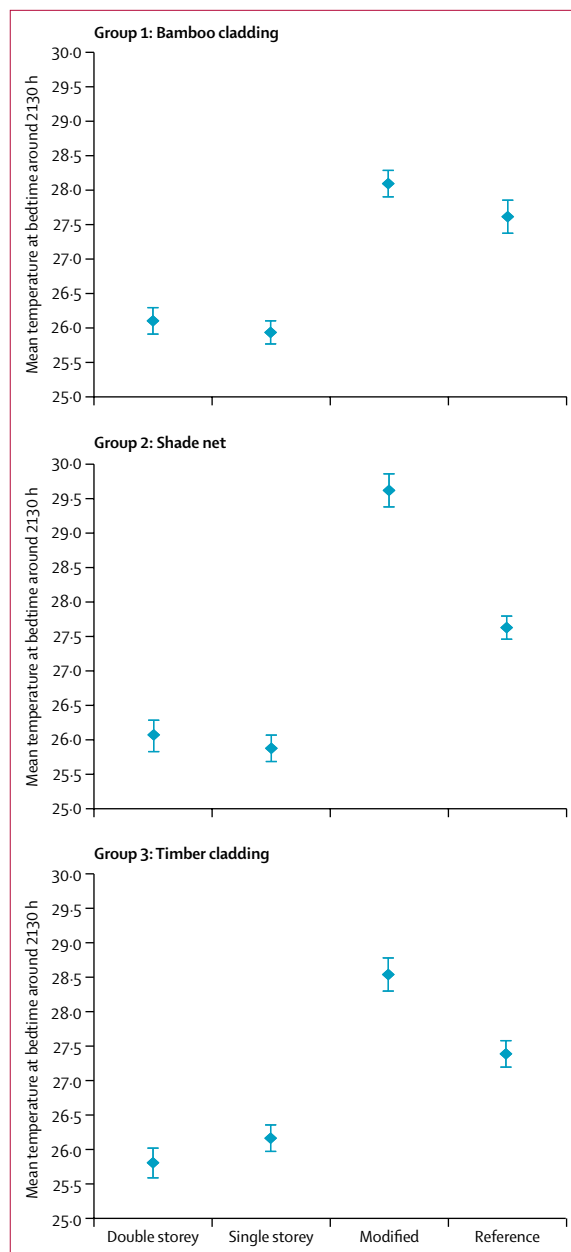


Figure 7: Summary of mean indoor temperature between August, 2015, and July, 2016, by house type
The whiskers indicate 95% confidence interval.

	Mean	Group 1: Bamboo	Group 2: Shade net	Group 3: Timber	Group 4: Thai
Single story	82	81	85	79	..
Double story	79	80	79	78	..
Modified	27	34	18	30	..
Reference	47	35	51	54	..
Thai bamboo	85	85

Table 3: Predicted mean vote (between Dec 1, 2015, and May 31, 2016, during the hours 1900 h to 2200 h)

codes were then used to guide the analysis of the transcripts, whereby meaningful segments of texts were assigned to their respective codes. Additional codes were generated as they appeared within transcripts during the coding process. The in-depth interview and focus group discussions transcripts underwent qualitative content analysis using NVivo software (QSR International, Melbourne, Australia).

An overall heat map that consisted of a matrix of the novel houses' construction cost, indoor bedtime temperature, reduction in indoor mosquito density and acceptability values was created to guide the selection of the most appropriate design for the scale-up of the project.

STATA 14.1 (StataCorp; 4905 Lakeway Drive; College Station, Texas 77845, USA) was used for statistical analysis of quantitative data.

Role of the funding source

The funder had no role in study design, data collection, analysis, or writing of the report. The corresponding author had full access to the study data and final responsibility for the decision to submit for publication.

Results

Between July, 2014, and July, 2015, three single-storey and three double-storey houses were constructed, one of each with the following claddings: bamboo (group 1), shade net (group 2), and timber (group 3; figure 2 and appendix). A Thai-Karen bamboo house and the teacher's house (group 4) were subsequently built between July and December, 2015. Images of the houses during the day and night illustrate the air and light permeability of the new houses (figure 4). The building costs were similarly low for the bamboo and shade net buildings and more expensive for the timber-clad houses (table 1).

The most frequently caught mosquitoes inside the prototypes were *Culex quinquefasciatus* (23 [34%] of 68) and in traditional houses *Anopheles gambiae sensu lato* (98 [34%] of 286; table 2). Outdoors, the most frequently caught mosquitoes in both prototype and traditional houses were *A. gambiae* s.l. (38%), followed by *Mansonia* species (21%) and *Culex quinquefasciatus* (18%). The overall reduction of all mosquitoes caught was highest in the double-storey buildings (96%, 95% CI 92–98) followed closely by the reduction found in single-storey buildings (77%, 72–82) and lowest in the modified reference houses (43%, 36–50) and unmodified reference houses (23%, 18–29; figure 5). The reduction of anophelines alone was also highest in the double-storey buildings (97%, 95% CI 92–99) followed by single-storey buildings (75%, 67–81) and lowest in the modified reference houses (33%, 26–43), and unmodified reference houses (3%, 1–7).

The mean bedtime indoor temperatures, between 2100 h and 2200 h, were highest between January and March, coinciding with the malaria season and

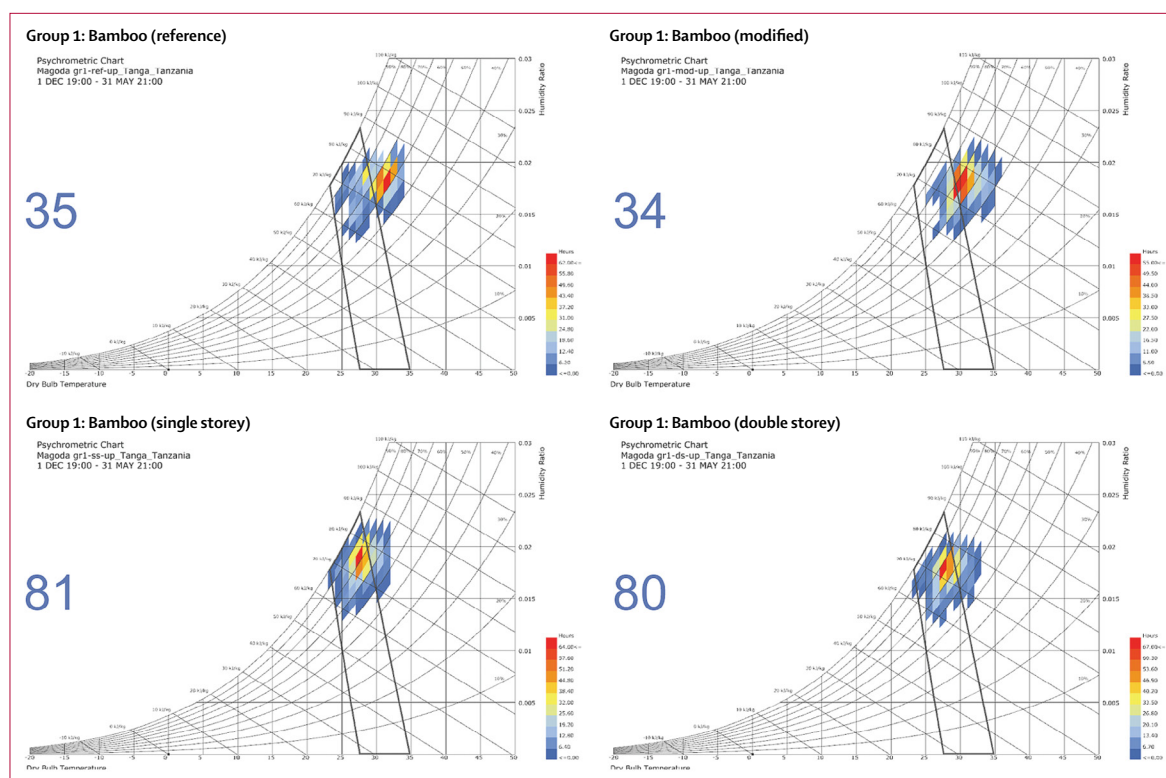


Figure 8: Predicted mean vote using the example of group 1 houses (between Dec 1, 2015, and May 31, 2016, between 1900 h and 2200 h)

lowest between June and August (figure 6). In January, 2016, the bedtime indoor temperature in the reference and the modified traditional houses reached up to 30.0°C between 2100 h and 2200 h. The mean temperature was 28.6°C (95% CI 28.3–28.8) in the unmodified reference and 29.8°C (29.5–30.1) in the modified traditional houses versus 26.8°C (26.6–27.0) in the double-storey novel design houses and 27.2°C (27.0–27.4) in the single-storey houses. The indoor temperature difference between the new design prototypes and the reference houses between 2100 h and 2200 h was 2.3°C (95% CI 2.2–2.3). Figure 7 showed the overall mean indoor temperature at bedtime between August, 2015, and July, 2016. The mean indoor bedtime temperature (26.0°C; 95% CI 25.8–26.2) was lower in the novel houses than in the matched modified or unmodified reference house (28.1; 27.9–28.4). Between Dec 1, 2015, and May 31, 2016, during the hours from 1900 h to 2200 h the mean comfort level measured as predicted mean vote, was 27% in the modified traditional houses, in the traditional reference houses 47%, in the double-storey houses 79%, and in the single-storey houses 82%. In comparison, the Karen style bamboo house had the highest comfort level percentage of 85% (table 3 and figure 8). Seven people who moved into the prototype houses and seven of their neighbours (three of whom had their houses modified) participated in in-depth interviews. After

	Cost	Indoor bedtime temperature	Reduction in indoor mosquito density	Acceptability
Shade net				
Double story	Intermediate	Best	Best	Intermediate
Single story	Intermediate	Best	Best	Intermediate
Timber				
Double story	Worst	Best	Best	Best
Single story	Worst	Best	Worst	Best
Bamboo				
Double story	Best	Best	Best	Worst
Single story	Best	Best	Worst	Worst

Table 4: The novel houses' construction cost, indoor bedtime temperature, reduction in indoor mosquito density and acceptability values

living in their new prototype houses for 6–9 months, residents expressed satisfaction with the new designs. When asked about their opinions of the different design elements, residents most commonly mentioned the second-storey sleeping area (five of seven participants), describing the room as cooler and safer from insects and crawling animals (including snakes) than in their previous homes (appendix). Two-storey buildings also offered more privacy than single-storey buildings. 33 adult male and female neighbours of the new houses participated in the focus group discussions. Overall, there was a preference for double-storey houses.

With regards to preference about the material used for cladding, four (57%) of the seven residents preferred the timber houses (group 3), which they regarded as secure, durable, and protective of privacy. The shade net houses were described as the second preference, especially in the two-storey configuration, which mitigated concerns about security and durability of this material. The bamboo houses were least favoured, with respondents reporting that an insect infestation of the bamboo walls produced, in some cases, an annoying dust. Respondents also felt that the bamboo cladding leaves gaps, which prevent complete privacy and can make it difficult to regulate airflow. By contrast, the residents of the Thai-Karen house, which in contrast to the prototypes was built using insecticide-treated bamboo, reported no problems with insect infestation. The focus group discussions confirmed a preference for timber and shade net cladding over bamboo cladding. Other concerns centred on the size of the new houses: although traditional homes tend to be smaller or of similar size to the new buildings, respondents said they preferred big houses to accommodate their extended families. Based on their appearance, neighbours expressed concerns about the construction costs and affordability of the new prototype houses.

The cheapest of the new buildings was the double-storey shade net building at US\$4661 and the most expensive building was the timber-clad double-storey building at US\$6125. The costs for unmodified traditional homes were estimated at US\$4231. The additional modifications including screened windows and water harvesting cost US\$1989.

Table 4 shows cost, temperature, mosquito density, and acceptability between the novel houses. Double-storey buildings performed best in reducing indoor mosquito densities and temperature. Timber cladding had the highest acceptability but is more expensive than other cladding materials. Double-storey buildings using shade net as cladding appear acceptable, well ventilated, relatively cool and protected from mosquito entry while less costly than timber-clad buildings.

Discussion

Our findings showed there were fewer mosquitoes in prototype southeast Asian homes compared with traditional African houses, that night-time temperatures were lower in prototype houses than in traditional homes, and that residents and neighbours felt positively about the new type of house design. Double-storey buildings did best in reducing mosquito densities because in sub-Saharan Africa generally mosquito density decreases with building height,^{34–36} with one study collecting at least 80% of the entire catch, from less than 1 m above the ground.³⁷ It might be the double-storey buildings were protective against mosquitoes because the space below the second storey reduced the ability of mosquitoes to locate a human host. Investments in

double-storey buildings are likely to provide protection against several mosquito-borne diseases, and encourage bednet use. This is of relevance when residents spend waking time indoors, while unprotected by a bednet.

With regards to the reduction in night-time temperatures in houses adapted to tropical conditions, ground elevation and permeable cladding materials were important design elements that contributed to this improvement. The psychrometric assessment highlighted the superior comfort level in the prototype houses compared to modified and traditional houses. The comfort level assessment was based on temperature and humidity. Improving airflow in the prototype houses should result in a further extension of the comfort zone and even higher comfort levels than reported here. The use of bednets all-night and all-year round for protection against malaria is likely to be enhanced in these cooler, more comfortable rooms.

The long-term success and sustainability of new architectural designs depends on the acceptance by their residents and neighbours. It is reassuring that a formal evaluation of residents' and neighbours' opinions found that the prototype houses were well liked. Their positive assessments of double-storey buildings, which have not traditionally been constructed in rural sub-Saharan Africa, including the study setting, are especially important. Although residents' positive opinions might have been affected by a desire not to disappoint the research team, such bias seems unlikely because the acceptability team was independent from the house construction team. The preference of new over old is strongly supported by the fact that none of the residents of new buildings moved back in their previous abode.

Residents and neighbours preferred the two-storey houses over single-storey buildings and the lowest mosquito densities were recorded in the upstairs rooms. Upstairs bedrooms also address user concerns regarding their privacy and security, provided that other double-storey buildings do not abut and overlook them. Shade nets are a new, low-cost building material, which are currently widely available for a range of purposes other than building materials. In houses that used shade nets both as cladding and to cover eaves, indoor mosquito populations were reduced (100% and 90% in double-storey and single-storey buildings, respectively). Importantly, reduction of indoor mosquito density was less pronounced in modified traditional houses with sealed eaves. Further adaptation of shade nets, specifically as building material in double-storey buildings, holds promise for affordable housing in rural sub-Saharan Africa.

Community members' negative attitudes towards bamboo as a construction material are unfortunate. Bamboo is a cheap and ubiquitous construction material throughout Asia hence there is considerable experience of how to use this material. Never previously used as a construction material in Magoda, there is no local experience of how to protect bamboo from insect attacks.

The bamboo house constructed by Thai craftsmen suffered few attacks from insects probably because of the pretreatment with insecticides, whereas the bamboo cladding used in prototypes remained susceptible to insect infestation. Before further attempts to employ bamboo as a construction material, there is now a need to understand which insects attack bamboo in Africa and how bamboo can be protected against such attacks.

Construction costs will play a critical role in the uptake of these new designs. The community showed a preference for timber, a traditional building material in the region which is more expensive than bamboo or shade net. With diminishing forests in sub-Saharan Africa it is reasonable to expect that timber prices will further increase in the coming years. In contrast, shade net is a novel material that is not yet widely used for facades in housing and may become more affordable through economies of scale. Bamboo, the cheapest of the cladding materials in the study is the most popular building material in rural southeast Asia but is underutilised in sub-Saharan Africa.

This was an early assessment of a novel house design to improve health. The study therefore has limitations. Six prototype buildings are not enough to show a clinical effect; hence no attempt was made to assess health benefits. Keeping the limited number of units for statistical inference in mind, proportions and their 95% confidence intervals are presented. A much larger sample size will be needed to detect a significant effect on mosquito numbers, indoor climate, and any potential health benefits. There was potential confounding between the two key measurements, indoor climate and mosquito counts, and geographic position. Although unlikely, it is possible that the new houses were constructed at sites with lower mosquito densities and cooler night-time temperatures compared with the surrounding control houses. Furthermore, mosquito densities were assessed over 4 nights only. It is possible that the benefits are less pronounced over longer observation periods. Nonetheless, the magnitude of the reduction in indoor mosquitoes in the novel designs was substantial, suggesting these are real effects. The cost of new buildings reported in this study includes building materials and cost of labour. Estimating the cost of prototypes is difficult due to the modifications arising during the building process. Labour costs are highly flexible if the future residents and neighbours contribute to the construction as is tradition in rural Africa. It is reasonable to expect that building costs drop when new design houses are built at scale.

The investments required for the construction of novel housing are orders of magnitude higher than—for example—a long-lasting, insecticide-treated bednet that costs around US\$2. However, the potential health benefits of novel design houses go far beyond those of insecticide-treated bed nets alone: (1) reduced mosquito density combined with a more comfortable environment for bednets to reduce mosquito-borne diseases; (2) permeable wall cladding and separation of cooking facilities to

improve air quality and to reduce the risks for respiratory tract infections including tuberculosis (not to mention accidental fires); and (3) the availability of safe water and latrines to prevent enteric diseases. Our findings show it is feasible and acceptable to local communities to build houses with a novel design in rural Africa that reduce mosquito house entry and keep the occupants cooler than traditional houses. With rapid population expansion and economic growth in sub-Saharan Africa there is an opportunity to provide healthier and more comfortable housing in rural Africa. There has never been a better time to modernise the housing stock in sub-Saharan Africa to construct dwellings that reduce the threat from vector-borne diseases and keep the house cool. Based on the overall heat map of the results, it would be reasonable to scale-up the construction of double-storey shade net buildings and assess their effect on multiple aspects of health, including mosquito-borne disease, respiratory illness, and enteric infections. Such investments must be based on findings that come from adequately powered, large randomised trials.

Contributors

LvS and JBK conceived the study. JBK designed the prototypes. KI adapted and implemented the designs. KI and SM supervised the construction. TEN and WNK did the entomological study. SWL advised on the entomological aspects and the overall interpretation of the study findings. SM supervised the acceptance study. CP advised on the analysis and interpretation of the qualitative study aspects. MM advised on the statistical aspects of the analysis. JLD advised on the study implementation. LvS, JLD, JBK, and SWL wrote the first draft of the report. All authors reviewed and edited the final report.

Declaration of interests

We declare no competing interests.

Acknowledgments

We thank the people of Magoda for their support of the study. The houses were built by local craftsmen. We thank the craftsmen for their dedication to this project specifically Kindo Ngumi, NMRI who implemented the construction work. SWL is supported by the Global Health Trials funded by the MRC-DfID-Wellcome Trust. We thank the Ruth W Jensens Foundation, Copenhagen, and Hanako Foundation, Singapore for their support.

References

- 1 UN. World Population Prospects. Key findings and advance tables. New York: United Nations, 2015.
- 2 Huho B, Briët O, Seyoum A, et al. Consistently high estimates for the proportion of human exposure to malaria vector populations occurring indoors in rural Africa. *Int J Epidemiol* 2013; **42**: 235–47.
- 3 Tusting LS, Bottomley C, Gibson H, et al. Housing improvements and malaria risk in sub-Saharan Africa: a multi-country analysis of survey data. *PLoS Med* 2017; **14**: e1002234.
- 4 Pulford J, Hetzel MW, Bryant M, Siba PM, Mueller I. Reported reasons for not using a mosquito net when one is available: a review of the published literature. *Malaria J* 2011; **10**: 83.
- 5 Fanger P. Thermal Comfort. Copenhagen: Danish Technical Press, 1970.
- 6 Koenigsberger OH, Ingersoll TG, Mayhew A, Szokolay SV. Manual of Tropical Housing and Building. Part One: Climatic Design. London: Longman, 1974.
- 7 von Seidlein L, Ikonomidis K, Bruun R, et al. Airflow attenuation and bed net utilization: observations from Africa and Asia. *Malar J* 2012; **11**: 200.
- 8 Knudsen JB, von Seidlein L. Healthy Homes in Tropical Zones: Improving Rural Housing in Asia and Africa (Hardcover). Fellbach, Germany: Edition Axel Menges, 2014.

- 9 Lindsay SW, Emerson PM, Charlwood JD. Reducing malaria by mosquito-proofing houses. Reducing malaria by mosquito-proofing houses. *Trends Parasitol* 2002; **18**: 510–14.
- 10 Gillies MT, Wilkes TJ. The vertical distribution of mosquitoes flying over open farmland in the Gambia. *Trans Roy Soc Trop Med Hyg* 1974; **68**: 268–69.
- 11 Axley J. Multizone airflow modeling in buildings: history and theory. *HVAC&R Research* 2007; **13**: 907–28.
- 12 Charlwood JD, Pinto J, Ferrara PR, et al. Raised houses reduce mosquito bites. *Malar J* 2003; **10**: 45.
- 13 Lindsay SW, Emerson PM, Charlwood JD. Reducing malaria by mosquito-proofing houses. *Trends Parasitol* 2002; **18**: 510–14.
- 14 Assad NA, Balmes J, Mehta S, Cheema U, Sood A. Chronic obstructive pulmonary disease secondary to household air pollution. *Semin Respir Crit Care Med* 2015; **36**: 408–21.
- 15 Piddock KC, Gordon SB, Ngwira A, et al. A cross-sectional study of household biomass fuel use among a periurban population in Malawi. *Ann Am Thorac Soc* 2014; **11**: 915–24.
- 16 Zambrano AI, Munoz BE, Mkocha H, West SK. Exposure to an indoor cooking fire and risk of trachoma in children of Kongwa, Tanzania. *PLoS Negl Trop Dis* 2015; **9**: e0003774.
- 17 Clasen T, Roberts I, Rabie T, Schmidt W, Cairncross S. Interventions to improve water quality for preventing diarrhoea. *Cochrane Database Syst Rev* 2006; **3**: CD004794.
- 18 Cairncross S, Hunt C, Boisson S, et al. Water, sanitation and hygiene for the prevention of diarrhoea. *Int J Epidemiol* 2010; **39** (suppl 1): i193–205.
- 19 Lindsay SW, Snow RW. The trouble with eaves; house entry by vectors of malaria. *Trans R Soc Trop Med Hyg* 1988; **82**: 645–46.
- 20 Knols BG, Farenhorst M, Andriessen R, et al. Eave tubes for malaria control in Africa: an introduction. *Malar J* 2016; **15**: 404.
- 21 Andriessen R, Snetselaar J, Suer RA, et al. Electrostatic coating enhances bioavailability of insecticides and breaks pyrethroid resistance in mosquitoes. *Proc Natl Acad Sci USA* 2015; **112**: 12081–86.
- 22 Lines JD, Myamba J, Curtis CF. Experimental hut trials of permethrin-impregnated mosquito nets and eave curtains against malaria vectors in Tanzania. *Med Vet Entomol* 1987; **1**: 37–51.
- 23 Kirby MJ, Ameh D, Bottomley C, et al. Effect of two different house screening interventions on exposure to malaria vectors and on anaemia in children in The Gambia: a randomised controlled trial. *Lancet* 2009; **374**: 998–1009.
- 24 Pinder M, Conteh L, Jeffries D, et al. The RooPfs study to assess whether improved housing provides additional protection against clinical malaria over current best practice in The Gambia: study protocol for a randomized controlled study and ancillary studies. *Trials* 2016; **17**: 275.
- 25 Tanzania National Bureau of Statistics. Tanzania Total Population by District Regions 2016. <http://www.nbs.go.tz/nbstz/index.php/english/statistics-by-subject/population-and-housing-census/844-tanzania-total-population-by-district-regions-2016> (accessed Aug 14, 2016).
- 26 Ceesay SJ, Casals-Pascual C, Erskine J, et al. Changes in malaria indices between 1999 and 2007 in The Gambia: a retrospective analysis. *Lancet* 2008; **372**: 1545–54.
- 27 Ishengoma DS, Mmbando BP, Segeja MD, Alifrangis M, Lemnge MM, Bygbjerg IC. Declining burden of malaria over two decades in a rural community of Muheza district, north-eastern Tanzania. *Malar J* 2013; **12**: 338.
- 28 Sadeghipour-Roudsari M, Pak M. LadyBug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. International IBPSA Conference; 2013; Lyon, France.
- 29 Govella NJ, Chaki PP, Geissbuhler Y, et al. A new tent trap for sampling exophagic and endophagic members of the *Anopheles gambiae* complex. *Malar J* 2009; **8**: 157.
- 30 Scott JA, Brogdon WG, Collins FH. Identification of single specimens of the *Anopheles gambiae* complex by the polymerase chain reaction. *Am J Trop Med Hyg* 1993; **49**: 520–29.
- 31 Wright EM, Royston P. Simplified estimation of age-specific reference intervals for skewed data. *Stat Med* 1997; **16**: 2785–803.
- 32 Rigby RA, Stasinopoulos DM. Smooth centile curves for skew and kurtotic data modelled using the Box-Cox power exponential distribution. *Stat Med* 2004; **23**: 3053–76.
- 33 van Buuren S, Hayes DJ, Stasinopoulos DM, Rigby RA, ter Kuile FO, Terlouw DJ. Estimating regional centile curves from mixed data sources and countries. *Stat Med* 2009; **28**: 2891–911.
- 34 Snow WF, Wilkes TJ. The height and direction of non-host oriented flight, and the age, of *Anopheles melas* in relation to wind direction in The Gambia, West Africa. *Trans R Soc Trop Med Hyg* 1970; **64**: 477.
- 35 Corbet PS. The age-composition of biting mosquito populations according to time and level: a further study. *Bull Ent Res* 1962; **53**: 409–15.
- 36 Corbet PS. Entomological studies from a high tower in Mpanga forest, Uganda. VIII. The age-composition of mosquito populations according to time and level. *Trans R Soc Trop Med Hyg* 1961; **113**: 336–45.
- 37 Snow WF. The vertical distribution of flying mosquitoes (Diptera: Culicidae) near an area of irrigated rice-fields in The Gambia. *Bull Ent Res* 1979; **69**: 561–71.