Malaria vector ecology and housing in The Gambia

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The Gambia

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Abstract

Malaria is a major health challenge in low- and middle-income countries in the Global South, especially in sub-Saharan Africa. In the last 50 years the combined distribution and appropriate use of insecticide-treated nets, insecticide residual spraying and mass drug administration campaigns dramatically reduced malaria cases globally. This reduction, however, has stopped and even reversed in some places. In the last decade, this concern has led to the exploration of innovative solutions for vector control and to the return of strategies like house modification, which were popular before the widespread use of insecticides that took place after World War 2.

In this thesis, I explored how several specific house-based modifications can reduce mosquito house entry, and possibly malaria infection rates, through a series of experiments conducted in two rural villages in The Gambia. Experiments conducted in Wellingara assessed the effect on mosquito hut entry and indoor temperature of raising an experimental hut above the ground and the effect of closing the ground floor in an elevated hut using four experimental huts. Studies in Wali Kunda explored how indoor temperature was affected by different roof colours and the effect on mosquito house entry and indoor temperature of passive and active ventilation in two experimental houses. Finally, a qualitative study assessed the routines that took place in the domestic space and how it relates to risk of malaria infection and vector control programmes.

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Abbreviations

AIDS	acquired immunodeficiency syndrome
CDC	Centers for Disease Control and Prevention
DDT	dichlorodiphenyltrichloroethane
GDP	gross domestic product
GNP	gross national product
IRS	indoor residual spraying
ITN	insecticide-treated net
MDGs	Millennium Development Goals
MRC	Medical Research Council
NGO	Non-governmental organization
PCR	Polymerase chain reaction
SDGs	Sustainable Development Goals
SSA	sub-Saharan Africa
USD	United States dollar
WHO	World Health Organization

Declaration

The work contained in this thesis has not been submitted elsewhere for any other degree or qualification and is the authors own work unless otherwise stated.

Statement of Copyright

Acknowledgements

First, I want to thank my supervisor, Steve Lindsay who has been a fantastic guide in this academic and life journey. Thank you for sharing your research station with me and for trusting me your ideas and allowing me to explore mine and for teaching me how to better communicate even with me trying to deviate from the point in every sentence I write. I am grateful for having a caring supervisor who not is not only interested in my academic development but in my overall wellbeing too, a supervisor who made this experience positive and full of learnings. I want to thank all my incredible supervisors who had taught me so much in these years and have accompanied my PhD journey. Hannah and Kate who supervised the qualitative part of my research, supported me emotionally and assured me that what I had to say was important. Anne who embraced the construction site for our project and is a constant inspiration with her youth and brilliance. Fiona who always had interesting ideas and points of view that enriched every question and research project. Jakob and Daniel who I profoundly admire for talking the non-conventional health path for people working in the built environment.

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Introduction

Malaria is a major health challenge at a global level, but specially in the African Region. In 2020 there were 241 million malaria cases reported of which 95 %, 228 million occurred in this region [1]. Similarly, 96 % of the 627,000 malaria related deaths on the same year occurred in Africa, mostly affecting children younger than 5 years [1]. Efforts to reduce incidence, elimination and eradication have been in the top priorities of the scientific international community and funding organisations for the last decades. The progress achieved in the last 40 years with the widespread use of insecticide treated nets (ITNs), insecticide residual spraying (IRS) and mass drug administration is threatened by stagnation in reducing malaria cases and, more recently, by the situation generated by COVID-19 [1,2]. Challenges faced before the pandemic included lack of proper use of ITNs [3,4], lack of ownership of an ITN [3], human behaviour affecting IRS [5] results and patients not adhering completely to pharmaceutical treatments [6] and insecticide resistance in some places [7]. The pandemic deepened this challenges by disrupting ITNs and treatment distribution chains, hindering access to health care and interfering with research and development projects [1]. A study predicting the worst scenario with 75 % disruption of both ITNs and malaria treatment forecasted that the incidence of malaria would increase by 21.5 % (46.4 million cases) and malaria related deaths would increase from 386,400 to 768, 600 due to the pandemic [8]. This regression calls for the implementation of innovate vector control strategies that can be maintained for years without external intervention, like infrastructure-based ones.

The relationship between the built environment and health has been explored by multiple cultures for centuries at the house and city scales. In relation to malaria, vector-control strategies based on changes to the built environment, such as house improvement and screening, drainage of lowlands and fish introduction were popular before the widespread use of laboratory created insecticides took place [9]. Strategies related to mosquito-proofing houses and environmental improvement were used in many parts of Europe and America as part of larger malaria control programmes [9,10]. Currently, these strategies have been overshadowed by successful integrated use of ITNs, IRS and pharmaceutical treatment. Consequently, allocation of financial resources for house-modification can be difficult as these interventions can be expensive, donors require more and stronger evidence to demonstrate its effectiveness and there is an implicit requirement of having results in a short term. Additionally, house modification to prevent malaria requires understanding of mosquito behaviour, human behaviour and how both of this intersect and interact in the built environment.

Most of the chapters (2 to 6) in this thesis explore house-based modifications to prevent malaria by reducing the numbers of mosquitoes inside the house and reducing indoor temperature, creating comfortable environments where people would be willing to use additional measures like ITNs [3]. Chapter 7 explores the qualitative aspects of the household routine and the families in two rural villages in The Gambia, identifying actors to be involved in different stages of intervention and research projects. The last chapter in this thesis summarizes the findings in the preceding chapters and gives recommendations for future research related to house-modification as a malaria vector-control strategy.

Aims and Objectives

Aim

To explore the effect of modifying infrastructure elements at the household level to prevent mosquito house entry and reduce indoor temperature.

Research questions

This thesis aims to answer the following research question: can house-based modifications reduce house mosquito density and indoor temperature in a sustainable and appropriate way? To address this question, there are specific questions to be addressed by selecting specific elements of a house:

1. Does elevating a house from the ground reduces mosquito house entry and reduces indoor temperature?
2. Does enclosing the ground floor decrease the effect of indoor mosquito density and indoor temperature reduction of an elevated house?
3. Would changing the colour of the roof in experimental houses reduce indoor temperature?
4. Does increasing screened areas in external walls decrease indoor mosquito density and indoor temperature?
5. Does active and passive cooling reduce indoor mosquito density and temperature in experimental houses?

Overall goal

To identify practical methods for reducing indoor biting by malaria mosquitoes by changing the design of the house, without compromising human comfort.

Specific objectives

- To find out if the numbers of malaria mosquitoes entering houses, and thermal comfort, changes in houses located at different heights (chapter 2).
- To test if mosquito house entry in raised houses is affected by barriers under the house (chapter 3).
- To evaluate if changing the external colour of a metallic corrugated roof can reduce indoor temperature and increase human comfort (chapter 4).
- To determine whether different amounts of screened surface in doors and windows affect the numbers of mosquitoes entering the house (chapter 5).
- To evaluate if ventilation methods, using solar chimneys and ceiling fans, can reduce indoor mosquito densities and indoor temperature (chapter 6).
- To describe how daily routines of people influence exposure to disease infection and to identify which groups are involved in specific activities (chapter 7).

Study hypotheses

- House height is directly related with mosquito-house entry since most mosquitoes fly less than one metre from the ground.
- The existence of vertical barriers under a house increases the number of mosquitoes in upper stories, because they provide protection from external elements and guidance for mosquitoes.
- Covering a metal roof with a layer of white paint decreases indoor temperature and human comfort levels.
- Mosquitoes are attracted to human odour inside the dwellings, having focal entry points makes it easy for mosquitoes to identify the source and get inside the house.
- Having elements that cool down the room decreases CO_2 levels, which increases comfortability and reduces the odour guide for mosquitoes.
- Due to activities assigned by traditional gender roles, there are concrete groups of people involved in specific activities and moments when they are more exposed to malaria infection than others.

Thesis Overview

Chapter 1 reviews the current situation of malaria globally and in sub-Saharan Africa. It describes the specifics of malaria vectors in the region and its control strategies, including the historic use of built environment modification for vector control and public health strategies.

Chapter 2 describes an experiment assessing the impact in mosquito density and temperature of raising an experimental hut 1 m, 2 m and 3 m from the ground compared to a control hut at 0 m.

Chapter 3 assesses the impact on mosquito density and indoor temperature of having the ground floor free, closed with air-permeable material or closed with solid material in a hut elevated at 2 m compared to a hut on the ground.

Chapter 4 describes the effect of having bare-metal, covered with red paint or covered with white paint roofs on indoor temperature.

Chapter 5 assesses the effect on indoor mosquito density and indoor temperature of screening windows and doors.

Chapter 6 describes the effect of two experiments on indoor mosquito density and indoor temperature. The first, reviewed the effect of a solar chimney, a passive cooling system, and the second, the effect of an electrical ceiling fans, an active cooling system.

Chapter 7 qualitatively explores the routines of the families in Wali Kunda and Wellingara and suggests actors and moments to be included in various programmes.

Chapter 8 discusses the main findings of the thesis, study limitations and recommendations based on the results of the previous chapters.

Contributions

Some of the work in this thesis is reproduced from published manuscripts in which Majo Carrasco-Tenezaca was the first author or co-author.

Chapter 2 was published as Carrasco-Tenezaca *et.al.* 2021 (Journal of the Royal Society Interface 18:178). Steve Lindsay conceived the study; Jakob Knudsen, Hannah Wood and Ottis S. Brittain designed the experimental huts; Mohammed Abdi, Musa Jawara and Majo Carrasco-Tenezaca oversaw construction; Steve Lindsay, Majo Carrasco-Tenezaca, Musa Jawara, John Bradley and David Jeffries designed the study; Majo Carrasco-Tenezaca collected field data Musa Jawara, Margaret Pinder and Umberto D'Alessandro contributed in field supervision; Majo Carrasco-Tenezaca, Steve Lindsay and John Bradley contributed in data analysis; Majo Carrasco-Tenezaca and Steve Lindsay wrote the manuscript.

Chapter 3 has not been yet published. Steve Lindsay conceived the study; Steve Lindsay, Majo Carrasco-Tenezaca, Musa Jawara, John Bradley and David Jeffries designed the study and Majo Carrasco-Tenezaca collected field data; field supervision was provided by Musa Jawara and Umberto D'Alessandro; data analysis was by Majo Carrasco-Tenezaca & John Bradley; Majo Carrasco-Tenezaca and Steve Lindsay wrote the manuscript.

Chapter 4 was published as Carrasco-Tenezaca *et.al.* 2021 (Malaria Journal 20:423). Steve Lindsay and Jakob Knudsen conceived the study; Ebrima Jatta, Musa Jawara and Margaret Pinder collected field data; Majo Carrasco-Tenezaca, John Bradley, Jakob Knudsen and Steve Lindsay contributed to the analysis. The manuscript was written by Majo Carrasco-Tenezaca and Steve Lindsay.

Chapter 5 was published as part of Jatta and Carrasco-Tenezaca, *et.al.*, 2021 (Journal of the Royal Society Interface 18:178) Steve Lindsay coordinated the study. Steve Lindsay, Ebrima Jatta, Majo Carrasco-Tenezaca, John Bradley, David Jeffries, and Jakob Knudsen designed the study. Ebrima Jatta, Majo Carrasco-Tenezaca, Balla Kandeh, Musa Jawara, Margaret Pinder and Umberto D'Alessandro coordinated the field studies. Ebrima Jatta and Majo Carrasco-Tenezaca collected data. Steve Lindsay, Ebrima Jatta, Majo Carrasco-Tenezaca, John Bradley, David Jeffries, Musa Jawara, Daniel Sang-Hoon Lee, Margaret Pinder, Anne Wilson and

Jakob Knudsen contributed to the data analysis and interpretation. Ebrima Jatta and Majo Carrasco-Tenezaca wrote the draft report.

Chapter 6 has not been yet published. Anne Wilson, Phillip McCall, Steve Lindsay and Majo Carrasco-Tenezaca conceived the study; Daniel Sang-Hoon Lee, Jakob Knudsen, Anne Wilson, Steve Lindsay and Majo Carrasco-Tenezaca designed the study; Anne Wilson, Matthew S Holmes, Musa Jawara and Majo Carrasco-Tenezaca built and installed the solar chimney; Majo Carrasco-Tenezaca collected field data; field supervision was provided by Musa Jawara, Margaret Pinder and Umberto D'Alessandro; Daniel Sang-Hoon Lee, Jakob Knudsen, John Bradley, Anne Wilson, Steve Lindsay and Majo Carrasco-Tenezaca contributed to the analysis and interpretation. The manuscript was written by Daniel Sang-Hoon Lee, Anne Wilson, Steve Lindsay and Majo Carrasco-Tenezaca.

Chapter 7 has not been yet published. Majo Carrasco-Tenezaca, Hannah Brown and Steve Lindsay conceived and designed the study. Majo Carrasco-Tenezaca collected and analysed the data. Majo Carrasco-Tenezaca, Hannah Brown and Steve Lindsay wrote the manuscript.

Chapter 1. Literature review

1.1 Summary

Malaria is one of the major killer diseases on the planet, its consequences are worst among populations living in vulnerable conditions, particularly pregnant women and children under five years old [11]. This disease is deeply bounded in the poverty circle; malaria increases the economic burden of people infected but also hits the poorest individuals living in endemic zones. The complexity of the transmission cycle, the vectors and its relationship with the natural and socio-economic environment makes it extra challenging to prevent and control the disease [12]. Multiple studies and policy documents have advocated for a multi-sectoral approach to target malaria, including establishing partnerships between the health and built environment sectors [13,14]. There is evidence that housing modifications can protect inhabitants from malaria as well as other vector-borne diseases. Housing improvements to reduce malaria transmission need to be developed and, if protective and affordable, included in larger malaria control programs.

1.2 Malaria as a global threat

In 2020 the World Health Organization (WHO) reported 241 million global malaria cases, of which 94 % occurred in the African region [1]. The cases in the region led to an estimated of 602,000 malaria related deaths, 96 % of the total. In the same year there was an increase of around 12 million malaria cases and more than 200,000 malaria related deaths compared with 2018 and 2019 [1,2,15] . The increase of the last two years follows a trend that started in 2015 but was aggravated by the COVID-19 pandemic.

Malaria is transmitted by female *Anopheles* mosquitoes, some of the most efficient vectors globally [16]. The transmission cycle depends on the presence of three epidemiological factors: the host (female mosquitoes or humans), the pathogen (malaria parasite) and the environment [17] which provides adequate conditions for mosquito breeding and for mosquitoes to come in contact with people. Of the five species of *Plasmodium* parasites that can cause malaria [18], *P. falciparum* and *P. vivax* [19] are the most prevalent and dangerous globally (Figure 1.1), are the most prevalent and dangerous. When a person infected with *P. falciparum* parasite does not seek treatment the disease can progress and even cause death [11].

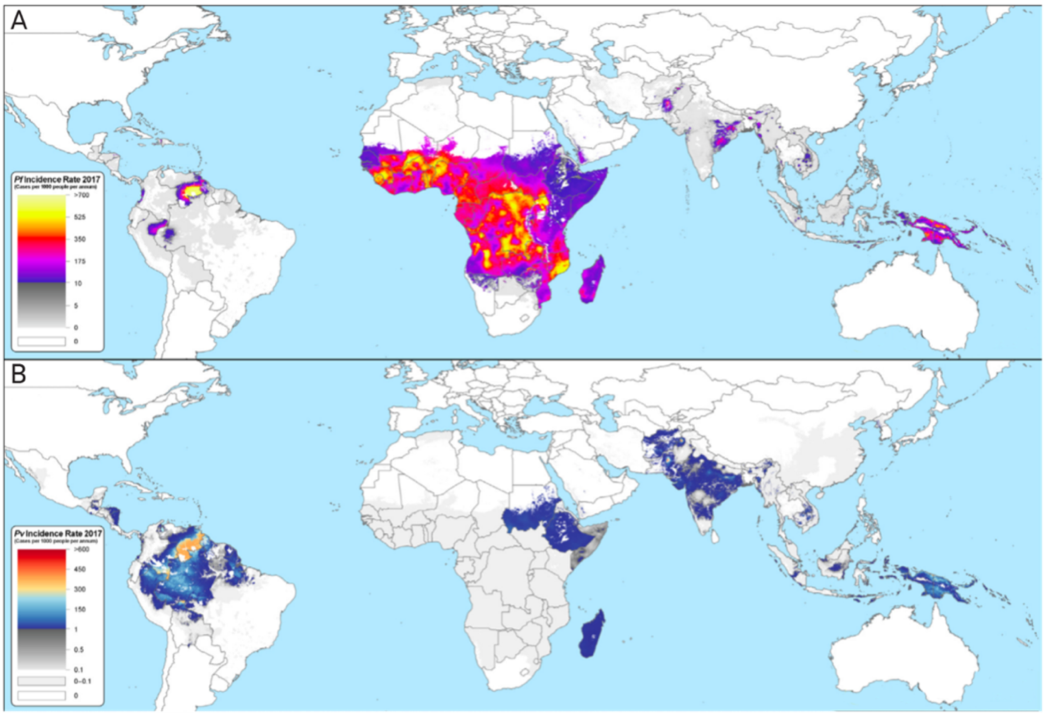

Figure 1. 1 Incidence of *Plasmodium falciparum* (A) and *Plasmodium vivax* (B).
Reproduced from *Plasmodium vivax* the era of shrinking *P. falciparum* map [19]

1.3 Effects on the economy

The relation between malaria and the economy is circular. Due to weak economies in many parts of the Global South, the environmental conditions are conducive for malaria infection. At the same time, malaria symptoms reduce the productive capacity of people, affecting their finances. Social and economic factors like sanitation, housing and poverty, are directly associated with prevalence of malaria in countries in the Global South [12,20]. The effects of malaria on the economy are so severe that after World War 2 the WHO recognized that malaria was affecting the development of industry and agriculture in the newly independent nations [21]. A comparative study conducted in 1995 revealed that the gross domestic product (GDP) for malaria endemic countries was, in United States Dollars (US$) 1,526, but only US$ 8,268 in non-endemic countries [22]. Countries that are malaria-free produce five times more than countries with malaria. Malaria has long-term effects on the level of gross national product (GNP) per capita, the total monetary value produced in the country. The GNP per capita of malaria non-endemic countries is more than double that of malaria endemic ones [22]. This means that production decreases because of malaria infection, with lost workdays and reduction in production. The reduction in work capacity that industry experiences is replicated at the household level too. While experiencing malaria symptoms, people tend to stay in their houses;

this contributes to increase the economic burden of families living from subsistence agriculture [23]. In fact, the highest levels of malaria infection occurs in the harvesting season, at the end of the rains [17,20], meaning that the economy of families that are already in a vulnerable position will be affected even more by hiring someone to work on their behalf or losing one day of harvest.

The economic cost of malaria can also be calculated by the amount of funding invested in the health sector. This includes provision of medicine, training of health personnel, improvement of facilities and research. In 2020, 3.3 billion (USD) were invested in malaria control and elimination and 619 million USD in research and development [1]. However, there is another cost of this disease; the amount of money countries lose or the amount invested by organizations. Malaria affects the future of individuals and nations. Malaria changes behaviour within the household. It does not only limit movement and work capacity of the sick but also interferes in the lives of other members that become caregivers. This usually has higher impact in the lives of girls and young women, who stay home taking care of the sick person and household chores, while missing school [24,25]. In the long term, they are more likely to leave school early, which can result in young and multiple pregnancies. For the family economy, having malaria translates into expenditure in medicine, traveling costs to the nearest health facility and loose in productivity. Low-income families have to spend their savings, if any, on malaria treatment which often takes priority over other expenses like school fees. Additionally, there is evidence that in areas with high child mortality families tend to have more children to ensure the survival of a number of them. With higher fertility rates, it becomes more difficult to have savings, send children to school or have access to adequate health systems. It has impact on girls education, who are seen as not a good investment because they will spend a large part of their lives taking care of kids which will decrease their ability to access to a job outside the household [26]. This in turn affects general education and health literacy of mothers, which creates a vicious circle with future generations.

On a country level, malaria reduces the nation's chances of foreign investment, affecting long-term growth [26]. Foreign companies are not likely to invest in malaria endemic countries because the nationals cannot perform at the required levels if they present multiple episodes of malaria during the year. In addition, foreign companies are less likely to expose people from non-endemic zones to malaria infection. Malaria also affects tourism within endemic countries. This is particularly important for the economies of places that are tourist destinations.

Malaria affects, slows down and interferes with many paths of development at the individual, community, national and regional levels.

1.4 The history and challenges for control of malaria

Malaria originated in Africa, from where it expanded to South-East Asia and Europe and reached the Americas during the 16th century with colonization [27]. With the discovery of dichloro-diphenyl-trichloroethane (DDT) in Switzerland in 1942 [27] and the success of indoor residual spraying (IRS) [27] it seemed that malaria could be eradicated globally. This hope was nourished by the success in malaria elimination in nations in the Global North between 1930 and 1950 [28] (Figure 2.2). The countries that achieved elimination were located in temperate regions and most of them were experiencing increased levels of socio-economic development at that time [26]. Compared with African nations, conditions in the North were different in climate zones, vector competence and economic status. The use of DDT and IRS with the inclusion of antimalarial drugs, were utilized in the 1955 Global Malaria Eradication Programme. Of which, the WHO excluded sub-Saharan Africa arguing that malaria elimination in that region was too problematic [29]. The program ran until 1969, after which the goal of malaria eradication shifted to malaria control. WHO revised its strategy to involve research and general services in its approach [27], and control strategies were advised to be based on local characteristics.

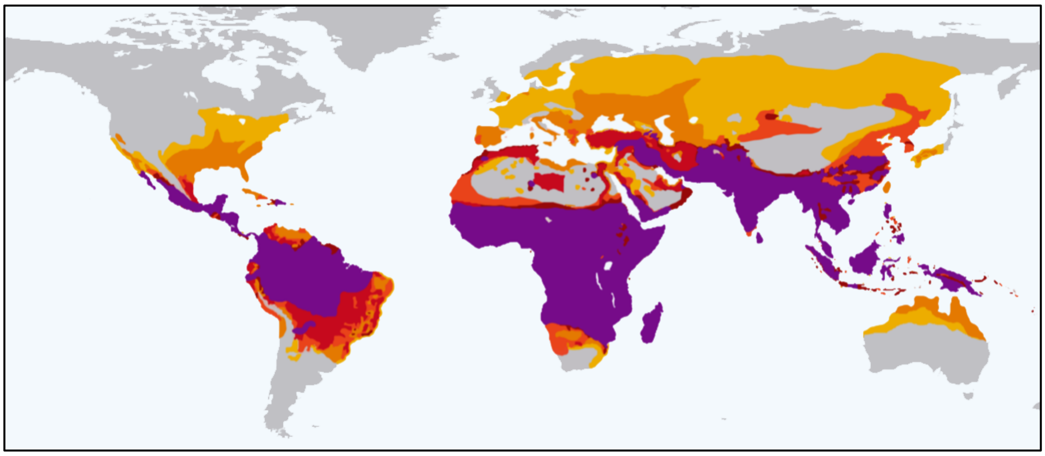

Figure 1. 2 Historical distribution of malaria.
Purple = malarious in 2002, dark red = malarious until 1994, bright red = malarious until 1975, red orange = malarious unitl 1965, orange = malarious until 1946, yellow = historical distribution of malaria until 1900 and grey = historically free of malaria [28].

This shift was also influenced by new conditions developed in the tropics, economic restrictions and social challenges [27]. The next major advance in malaria control, insecticide-treated nets (ITNs), was developed after the emergence of pyrethroids, insecticides that were safe, effective and long-lasting [30]. The use of

ITNs was first recommended for pregnant women and children [31] and fully recommended for the use of all population at risk and to be distributed freely or highly subsidised in 2007 [32]. Progress achieved with the use of ITNs and IRS led to a decrease in global malaria cases. Consequently, the Framework for malaria elimination stated that between 2000 and 2015 seventeen countries were declared malaria free and malaria cases declined by 37 % and malaria related deaths by 60% globally [33]. Countries that were on track of eliminating malaria from their territories experienced a regression in their progress due various factors, COVID-19 pandemic being the strongest in the last years[1]. Since 2000, elimination has been achieved in 43 countries, the majority of them in temperate zones and in the Global North (Table 1.1).

Table 1. 1 Countries certified as malaria free by the WHO between 2000 and 2021.

Year of WHO certification	WHO Region	Country
2007	Eastern Mediterranean	United Arab Emirates
2010	Eastern Mediterranean	Morocco
	Europe	Turkmenistan
2011	Europe	Armenia
2012	Africa	Lesotho, Seychelles
	Eastern Mediterranean	Bahrain, Jordan, Lebanon, Lybia, Qatar, Tunisia
	Europe	Albania, Andorra, Belarus, Estonia, France (Metropolitan), Greece, Israel, Kazakhstan, Latvia, Lithuania, Luxembourg, Republic of Moldova, Russian Federation, Ukraine
	Americas	Antigua y Barbuda, Bahamas, Saint Kitts and Nevis, Saint Vincent and the Grenadines, Uruguay
	Western Pacific	Japan, Kiribati, Tuvalu
2015	South-East Asia	Maldives
2016	Europe	Kyrgyzstan
	South-East Asia	Sri Lanka
2018	Europe	Uzbekistan
	Americas	Paraguay
2019	Africa	Algeria
	Americas	Argentina
2021	Americas	El Salvador
	Western Pacific	China

From 2000 to 2015 the number of malaria cases in sub-Saharan Africa was reduced by 40 % [34], largely due to the massive deployment of ITNs, IRS and prompt and effective treatment with antimalarials. This massive deployment of vector control and treatment was a result of the multilateral commitment fostered by commitment to the Millennium Development Goals (MDGs) and the Roll Back Malaria initiative [34]. In sub-Saharan Africa, half of the people at risk had access to an ITN within their household, but only 34% of the households had at least one treated bed-net for every two people [1]. In 2019 and 2020 there was a progressive decrease in ownership and reported use of ITNs, even though manufacturers reported an increase of ITNs deployment compared with 2018, with 229 million ITNs distributed in 2020 [1,2]. The main cause for this inconsistency in data is the effect that the COVID-19 pandemic has had over ITNs distribution programmes at national level. This phenomenon has occurred as a result of poor coverage of ITNs, lack of net durability and bio efficiency, development of insecticide resistance and changes in weather [4], meaning that the elements that successfully reduced malaria incidence in the past century are no longer effective and that the need for innovative ways for malaria control is becoming more urgent.

1.5 Challenges in malaria control in sub-Saharan Africa

Malaria is entrenched in sub-Saharan countries because of highly efficient malaria vectors, a climate that suits transmission and widespread poverty. The region was classified as too problematic due to different factors, some of which continue until this day.

1.5.1 African mosquito vectors

Members of the *Anopheles gambiae* complex and *An. funestus* complex are responsible for nearly all cases of malaria in sub-Saharan Africa [35]. Within each complex, each species has adapted to a specific environment and has developed behaviours to locate different blood sources. Anthropophagic mosquitoes find people using at least two of three indicators: chemical cues, specifically carbon dioxide and humans specific volatiles, vision and heat [36]. At long distances of around 10 m carbon dioxide can alert a mosquito to the presence of a possible blood source [37,38]. The maxillary palps in mosquitoes can detect a variation in carbon dioxide concentrations of 50 ppm [39] which can be intermittent due to wind currents. At distances close to a host, malaria vectors navigate upwind guided by odour plumes and enter a house through the open eaves [40,41]. Experiments have shown a doubling of *Anopheles* mosquitoes collected using a combination of carbon dioxide with human odours compared with carbon dioxide alone [42].

At a closer range, up to 2 m [43,44], a combination of chemicals, including lactic acid, sebum and skin microorganisms, released through the skin and visual cues are used to navigate towards a blood source [37,38]. When the mosquitoes are close to the scent source, they incorporate vision to hover nearby and land on the host [39]. The last indicator in the blood-finding process is heat, which can be detected at 0.15 m from the host [45]. *Anopheles* spp. has developed a receptor to avoid cool temperatures, helping to locate heat sources by discard [46], which might be the reason for them feeding on people during the early morning when people are asleep [35]. Female mosquitoes of the *gambiae* complex prefer to bite on the legs and feet when the hosts are sitting and head, trunk and arms when they are closer to the ground than the lower part of the body [47]. This behaviour might be guided by air currents that are lower closer to the ground than at higher levels where mosquitoes might not be strong enough to fly against the airflow. When following an odour mosquitoes fly at speed of 0.25 m/s [48] and they can maintain their flying route with air velocity up to 0.5 m/s [49]. Wind velocity higher than this level, however, is unlikely to be found indoors a rural household.

Mosquito and human behaviour shape the moments where malaria transmission occurs. For example, *An. gambiae* lay their eggs in human made sites that hold water including puddles, tyres tracks [50], borrow pits [51] and rice fields [16,52]. Sleeping exposed to the environment and close to these sites would increase the risk to be infected with malaria. Another example of this close relation, is related to the term "human-made malaria", when human activities produce places that are suitable for mosquito breeding and development [17]. In tropical regions suitable natural habitats for mosquitoes to breed is related to puddles formed during the rainy season, human made habitats are related to construction of new houses[53], pits and drains in gardens and close to houses [54]. If water gathers, it is likely that mosquitoes make of it a breeding place.

The vector feeding and resting habits are crucial in the transmission cycle. Anophelines feed between dusk and dawn, and sometimes during the day in dark environments, like dark interiors of houses [17]. Dark places are also day resting spaces for blood-fed mosquitoes because of their temperature and protection [17,55]. Specifically, mosquitoes rest on the walls, roof, hanging clothes or on pieces of furniture [17]. This is especially important when it comes to children getting malaria, as they are a vulnerable group [11,56] and spend a large amount of time indoors or close to the household. Another important factor is that *An. gambiae* feed predominantly indoors at night [16]. Mosquitoes and humans constantly share spaces and time which allows malaria transmission to occur between them.

1.5.2 Climate

Human as well as mosquito bionomics are highly influenced by environmental factors, this is of high importance for malaria control and prevention. Mosquitoes, especially in their early stages, are very sensitive to temperature, rainfall and humidity [57]. Larvae develop into adults between 16 ºC to 34 ºC and their survival time was longest when temperatures ranged between 14 ºC to 20 ºC, but when they increased by 2 ºC the survival rate decreased [57]. *Anopheles* mosquitoes are ideally adapted for temperatures experienced in tropical regions where mosquito population and malaria cases increase during the rainy season with the proliferation of aquatic habits [17]. Rainy season also increases the survival of female *Anopheles* due the higher levels of relative humidity and promotes the development of parasites in the mosquitoes due to the equitable temperature [20]. Adult mosquitoes are also affected by extreme temperatures. A study in The Gambia showed that adult *An. gambiae* mosquitoes in laboratory conditions moved away of surfaces that reached 33 ºC, the experiment also showed that mortality increased when mosquitoes were exposed to constant temperatures of 35 ºC [58]. In the same study, several Gambian villages showed that mosquito mortality was 38 % higher in metal-roof houses than thatched houses, where metal-roof houses were 1ºC hotter than thatched roof houses, probably affecting the metabolism of adult mosquitoes [58]. The environmental factors that impact mosquitoes also influence the incidence of malaria.

1.5.3 Socioeconomic limitations

Malaria mostly affects people living in rural areas of the tropics and sub-tropics where some of the poorest countries of the globe are located. People living in areas where risk of malaria is high often do not have access to health care facilities due to financial constraints, mobility issues or a combination of both. In many cases attending a health centre means losing one working day, something that people living hand-to-mouth cannot afford [23]. Additionally, health facilities in countries in the Global South can be poorly equipped and lacking appropriate medicine and treatment. This is a common trend in some countries, where health systems because the national economic situation lack the funding they need to function properly. Central governments reducing funding from their health and education systems is usually a consequence of structural adjustment programs, where even some of this services fall into non-governmental organizations (NGOs) [59]. People living with economic difficulties are forced to choose among basic needs and feeding and health often take priority over education and shelter [60]. A poorly-built house can increase the chances of malaria infection in regions where mosquitos feed indoors [41,61], it increases the time that people spend cleaning and fixing it and hinders performing tasks related to personal development and education [62]. Malaria is not only about a clinical diagnosis, but also is highly influenced by socio-economic factors too.

1.6 Control limitations

ITNs along with IRS, have contributed to the decrease of around 40 % cases of malaria between 2000 and 2015 [34], becoming the main element in vector control programs in sub-Saharan Africa. Since then, the progress has been slower and in the last two years there has been an increase of malaria cases globally [1,2,63]. Some argue that this counterproductive effect is due to mosquitoes developing insecticide resistance to the pyrethroids used in the ITNs [7]. However, there are many other reasons that affect the protective effect of ITNs. The first, and probably the one that has had the most impact in the increase of malaria cases in the last two years because of the COVID-19 pandemic is poor coverage of ITNs [1]. Manufacturers report a higher number of ITNs deployed in risk areas every year compared with the number of ITNs distributed [1]. This might be because the ITNs deployed during the last quarter of the year are usually delivered during the first quarter of the following year due to logistics challenges or time constraints [1]. With the emergence of the COVID-19 pandemic and the mobility measures in place globally almost every supply chain broke down, including ITNs distribution programs at local and national levels [1]. This meant that programs that have been planned for years ahead were set back and people needed an ITN might not get one until later than planned. People's behaviour is also a factor in ITNs not providing protection as they should when used properly. In rural areas of the Gambia, adults go to sleep around midnight [64]. Before that time, they stay outside their houses until it is cool enough to get inside and sleep, a time when they are exposed to mosquito bites. Other people do not use a bet net once they get inside their house because it is too hot [3] and the bed-net decreases the comfortability sensation even more [65]. Recently, issues about ITNs low bio-efficacy have emerged, which is the element that differentiates ITNs from non-treated nets and the one that contributes to reducing mosquito population. Several studies have suggested that, now, bed-nets are not manufactured according to WHO standards, which makes it harder for mosquitoes to die after being in contact with the ITN and consequently do not reduce mosquito populations [66]. Low durability of bed-nets due to the use of poor materials, might have also contributed to people not using a the ITN when it is beyond repair or to mosquitoes breaking the bed-net barrier by holes unnoticed by users [67,68].

1.7 Malaria transmission in relation to the built environment

Living in a modern house reduces the chances of getting infected with malaria by 47 % compared to people living in traditional houses [41]. In sub-Saharan Africa this is extremely relevant because the main malaria vectors in the region, are mainly active at night and feed on people resting indoors [17]. Elements of the building associated with modern housing, such as solid walls, roof and floor, screening windows, closing eaves and having a ceiling were all associated to reduction of odds of malaria infection or clinical malaria. Using screens in façade surfaces of the house increases ventilation and comfort while decreasing indoor mosquito density [69]. When people feel more comfortable their respiration [70] and metabolic rate [71] are more stable producing less carbon dioxide resulting in fewer mosquitoes being attracted to the house. Comfort levels inside a house depend on a combination of temperature, air humidity and wind speed [72]. In the tropics the thermal sensation of heat increases because of the high levels of humidity and low wind speed indoors. In chapter 5, having screened windows reduced indoor temperature by 17 % compared to no windows and increased indoor comfort levels, which was reflected in 38 % less indoor mosquito density [69]. Increased ventilation makes people cooler and diffuses carbon dioxide and odour plumes inside the house, making it more difficult for vectors to find odour plumes from afar.

Carbon dioxide (44.01 g/mol) is heavier than oxygen (15.99 g/mol) and therefore tends to sink below the layers of oxygen, which suggests that it first leaves the house through gaps at ground level of badly fitting doors depending on ventilation and airflow. In rooms with insufficient ventilation carbon dioxide builds up [73,74] and might leave the room or house through gaps at window level. Most measurements of indoor carbon dioxide concentration are done with highly sensitive loggers [75] and modelling is performed by introducing spatial and atmospheric data in computational fluid dynamics (CFD) software [74]. Because CFD modelling is relatively new, it is common that logger measurements are used to confirm modelling results. To be detected, it is important that these odour plumes have a higher concentration of carbon dioxide compared to environmental levels. In

1999 daily atmospheric carbon dioxide levels were measured in 367 ppm [76], while the night average levels in our experiments was 588 ppm.

Mosquitoes approaching a house do not fly higher than one metre above the ground [40,77]. As they approach the house, they fly up, entering the house horizontally through the eaves [78]. When mosquitos are inside the house the odour and carbon dioxide sources can be difficult to identify because plumes might accumulate and be static due to the reduction in the airflow of interior spaces [39]. Because of this, at a close range and in indoor spaces mosquitoes activate other methods like vision to identify the blood source. It is common that these mosquitoes rest indoors attracted by surfaces that have been in contact with the host (e.g. clothing, bedding) and wait for opportunistic feeding [39]. Because vectors in this region have evolved to feed when people are sleeping, and are at their most vulnerable, it is important to design strategies to protect people inside the house by keeping mosquitoes out. Additionally, resting inside traditional thatched-roofed houses offers stable and more benign atmospheric conditions compared to outdoors, helping to reduce the mortality of indoor-resting mosquitoes [79,80]. In rural Africa, houses have a higher mean temperature than the one outside helping the parasite development process [81]. It is more likely that mosquitoes prefer to rest close to the roof [82] and in thatched houses because of the porosity of the roof material even when metal roofed houses are warmer [83]. In The Gambia, metal roofed houses reached a temperature of 35° C, which forced mosquitoes to move from the hot roof nearer to the ground and increased mosquito mortality by 38 % after 24 h compared with thatched roof houses [58].

Recent recommendations have been made for protecting homes from mosquitoes that is captured in the DELIVER mnemonic: screened and well fitted Doors, closed Eaves, Lifted houses or sleeping quarters, use of Insecticide treated bed-nets, good Ventilation, Environmental management and solid Roofs [84]. Closing eaves in thatched-roof houses reduced malaria house entry by 94 % and by 96 % in metal-roofed houses [83] but it also increased indoor temperature. With a combination of strategies, it may be possible to find improved and modern houses that can also be comfortable for people to stay, sleep and live in. Fortunately, rural housing in sub-Saharan Africa has improved to 11 % to 23 % between 2000 and 2015 [85]. People are willing to invest in improving their houses or building them up with better materials and that impact malaria infections for their users.

1.8 International policy

In 2016, United Nations General Assembly concluded the era of the eight Millennium Development Goals (MDGs) and countries committed to the seventeen Sustainable Development Goals (SDGs) [86]. Both share similar goals in relation to poverty alleviation, increase of quality education and its scope and elimination of major diseases. The SDGs transformed some combined MDGs as individual ones (e.g. “Eradicate extreme poverty and extreme hunger” to “No poverty” and “Zero hunger”) or included them within the specific targets of each SDG (“Combat HIV/AIDS, malaria and other diseases” included in “Good health and well-being). The SDGs also illustrate better how one objective within a specific goal can have a positive impact in other goals and how collaborations between goals are important, a point evidenced in SDG 17: Partnerships for the goals. For example, achievement of malaria elimination would contribute to objectives of 16 of the 17 SDGs [63]. As well as the effects of eliminating malaria would be cross-disciplinary the efforts, strategies and approaches to its control and elimination should be inter- and multi-disciplinary. SDG 11 related to Sustainable cities and communities, could have a big impact in malaria prevention. Even when it seems that the main goal of SDG 11 is focused on cities, it really calls for an effort in human settlements in general, them being rural, semi-urban or rural. According to the World Malaria Report 2019, “well-planned infrastructure and improved housing help reduce exposure to mosquitoes, and facilitate greater access to health and malaria services” [63]. This SDG states the importance of access to adequate and safe housing and basic services and to green spaces, both of them linked to SDG 3 - Good health and well-being.

Later the same year, the New Urban Agenda was developed with an specific mention of making cities and human settlements healthy [87]. In the declaration there is mention of specific elements that link built environment and health like access to water and sanitation, adaptation to climate change, waste disposal, ambient air quality and end of open defecation. The document also states the commitment to follow interlinked principles and specifically mentions “ending epidemics of acquired immunodeficiency syndrome (AIDS) tuberculosis and malaria” although it doesn’t develop the idea further or explains how the built environment will contribute specifically to this. The only mention to risk to vector borne diseases is made when discussing challenges of cities in the Global South. The guidelines produced by international organizations make important initial contributions but lack scientifically proved, locally and culturally specific strategic suggestions for vector control in the build environment.

1.9 A case of international development

Malaria control require large investments of financial and human resources, logistics and organization. Sachs argued that a coordinated effort under WHO administration would encourage donor countries and philanthropic foundations to invest, knowing that the efforts were following the same direction and were coordinated by an institution backed up by science [88]. As a result, the Global Fund was created in 2002 to fight AIDs, tuberculosis and malaria. Others advocated for the development of programs to target different vectors at the same time, like developing a comprehensive program to target mosquitoes carrying filariasis, yellow fever and malaria with the same intervention [89]. Similarly implementing programs that use permanent measures was proposed as a long term solution, because the high capital invested can be balanced with low maintenance cost and indirect benefits [21].

Housing is an example of utilization of permanent measures to prevent disease. Countries that achieved malaria elimination in the 1950s, implemented a combination of efforts including environmental management, housing improvement, antimalarial interventions and socioeconomic measures [26]. Even though housing projects undoubtedly need more investment than conventional methods, they are also a long-term response tackling problems related not only to disease transmission but also to socioeconomic conditions and development. Therefore, house-related interventions could be funded not only by the health sector but by other means as well. Lack of water and sanitation infrastructure and poor housing conditions are the main infrastructural and spatial causes for diseases being more prevalent in impoverished environments[88,90]. Informal settlements are more likely to harbour diseases, affecting people with limited access to health facilities and treatment. Housing programs to prevent malaria should be developed from a policy effort, working along with specific vector control campaigns. In this way, it will be ensured that that activities develop in a long-term timeframe with holistic objectives [91].

1.10 Links between the built environment and public health

Architecture and urbanism have long been associated with health standards and condition of the population [92,93]. One of the main European examples of the relationship between environment and health was Ebenezer Howard's garden cities [94]. His idea was to create a space where the green of the rural areas and the modernity of the cities could coexist, leaving out the backwardness of the countryside and the chaos and overcrowding common in early Victorian cities [95]. The garden city idea had considerable influence in many places and continues to influence design in modern cities. In the Global South, these movements shaped the urban and rural layout during the modern period. Entire cities, like Brasilia in Brazil and Chandigarth in India, were built from scratch with the idea of creating improved and healthy environments. Clearance of informal settlements in Caracas, Hong Kong, Rio de Janeiro and Singapore City are some of the most relevant examples of modifying human settlements to fulfil the objectives of the new movements [96,97]. The modern period also aimed to provide schools and health centres in rural areas and to modify the pre-existing ideas of social housing in major cities of the Global South.

Traditional construction aligned with knowledge in use of local materials and thermal comfort have contributed to improving health for centuries. Specific traditional examples of environment linkages with health from the African Region come from the Chagga and the Nyakusa tribes in East Africa, who lived in highland areas and refused to move to lower locations or to coastal plains due fear of contracting malaria and of a large part of their population dying [98]. Recently, international organizations have identified strategic points in which housing and urban layouts can improve the health of the population. In an effort to communicate, share knowledge and improve conditions in this area they have created multiple reports [90,99], but implementation remains a challenge.

Current guidelines preventing malaria cases from the built environment perspective are based in previous strategies like having screened windows and ceilings underneath the roof, plastering walls and closing eaves [21,99]. Access to electricity to provide light and fans, has also been shown to be protective against malaria [21], as it is directly associated with indoor comfort and gives people the option of doing activities indoors rather than outside the dwelling. These recommendations are supported by a systematic review and meta-analysis where people living in improved houses had a 54–65% lower incidence of clinical malaria and 42 % lower odds of malaria infection compared to people living in traditional homes [41]. A related review found that houses classified as modern were likely to already have in place the strategies to prevent malaria [84]. Despite the improvement in housing conditions in sub-Saharan Africa [61] most infections occur indoors [100].

This might be due to various reasons: completely closing a house reduces ventilation and increases temperature [83,101], preventing people from sleeping under a ITN [3]; lack of screening in windows that act as a barrier [84], increases ventilation and human comfort [69] and reduces carbon dioxide levels used by mosquitoes to locate a host [37] and use of modern materials without the complete technological transfer like metal corrugate roofs [85] without adequate ventilation and cooling systems that allow people to inhabit those spaces night [83,102,103]. Improved housing should not be seen as an alternative to other vector-control strategies but as a complementary measure [84] that increases the effect of strategies already in place and contributes to keeping malaria mosquitoes out of the house. These measures will not protect people against malaria vectors only but from a variety of other insects capable of transmitting yellow fever, dengue, Zika, Chagas disease, among others.

1.11 Context of this research

The data for this thesis were collected in two rural villages in the Central River Region (CRR) in The Gambia, West Africa. The Gambia is located in the tropics and has its rainy season between June and October [104]. As a consequence, malaria transmission occurs between August and November [105] and the highest number of cases and deaths between September and November [106]. Both villages are located close to a large area of irrigated rice fields and 2.1 km apart from each other. The combined population of both villages was 671 people (Gambian census data 2013), the last census, of which most are of Mandinka ethnicity, with a smaller proportion of Fula ethnicity. Studies involving the experimental houses took place in Wali Kunda (N 13º34.25, W 14º55.28', while studies with the experimental huts were implemented in Wellingara, (N 13º33.36', W 14º55.46'). The qualitative data were collected in both villages. Before starting the data collection process, the field team asked for the *Alkalo*`s approval. The *Alkalo* is the village leader who has inherited his position from his father or elder brother.

Previous studies in the same location have inspired the experiments in this thesis. Experiments presented in chapters 2 and 3 assessed the hypothesis of vertical distribution of flying mosquitoes conducted in The Gambia [40,107] and Sao Tomé [108]. I found no laboratory experiments exploring how mosquitoes distribute vertically when seeking a host. Chapter 4 presented the importance of roofing colour in relation to thermal comfort and malaria transmission. There are several studies on this topic related to reducing energy consumption for cooling buildings [109–111], although they have not been related to communicable diseases. Chapter 5 discussed the cooling effect of mosquito screening a house compared to solid surfaces. Studies on breathing wall, a wall that allows the pass of airflow from inside and outside to reduce pollutants, [112] and porous wall materials [113] improving ventilation, support our findings on porous façades in increasing indoor ventilation. Nonetheless several laboratory studies have been conducted in use of screened mesh in reducing airflow in wind tunnels. [114] or greenhouses to prevent mosquito entry [115] which are useful when applying computational fluid dynamics (CFD) modelling. The active ventilation experiment in chapter 6, is related to wind tunnel experiments exploring the flying speed [116] of mosquitoes and their resistance against air current [48,49]. Conducting experiments related to housing and malaria transmission is challenging because they depend on atmospheric and environmental conditions specific to each place. Semi-field housing experiments are one way of performing housing experiments in semi-controlled conditions. Several experiments assessing the effect of light and ventilation in house entry [117], trap performance [118] and eave tubes [119] have taken place in Ifakara Health Insititute in Tanzania [120]. There are laboratory experiments that can be applied to research on housing and malaria transmission, especially related to carbon dioxide production [121,122] , diffusion and odour dispersion [45,122,123]. Another way to translate housing experiments to controlled-laboratory conditions is to study the microclimates existing inside the houses. The experiments presented in this thesis, however, assess conditions as close to real life as possible keeping in mind that a house is much more than its infrastructure and that human behaviour plays a large part in exposure to disease vectors.

Chapter 2. Does house height affect mosquito house entry? An experimental study in rural Gambia

2.1 Abstract

2.1.1 Background

In sub-Saharan Africa, 80% of mosquitoes in open grassland fly less than one metre from the ground. Here we tested the hypothesis that houses raised from the ground could reduce the house entry of mosquitoes, specifically *Anopheles gambiae*, the main vector of malaria in the region, and make the house cooler.

2.1.2 Methods

Four identical experimental huts, that could be moved up and down, were constructed in a line. Each week one hut was positioned at a height of 0 m, 1 m, 2 m or 3 m. Each night, two volunteers slept under separate bed-nets in each hut, and mosquitoes were collected indoors using one light trap. Indoor climate and carbon dioxide was monitored using data loggers. Sleeper pairs were rotated nightly between huts. Hut heights were changed weekly for 10 weeks. Primary measurements were mean number of *An. gambiae s.l.* and mean temperature for each house height.

2.1.3 Findings

A total of 1,015 female *An. gambiae* were collected at 0 m, 601 at 1 m, 333 at 2 m and 131 at 3 m. Multivariate analysis, adjusting for confounders, showed hut entry by *An. gambiae* declined by 0.60 (95% CI 0.47-0.76) at 1 m, 0.32 (95% CI 0.26-0.40) at 2 m and 0.16 (95% CI 0.11-0.23) at 3 m, compared to the hut at 0 m. Similar patterns were found with *Mansonia* spp., but not *Culex* spp., whose numbers were unaffected by hut height. Indoor temperature declined with increasing altitude. From 21.00 to 23.30 h, the house at 3 m was 0.10 °C cooler than the house at ground level, and from 00.00 to 07.00 h, 0.20 °C cooler. Comfort levels before midnight were greater in elevated huts than those on the ground. Modelled data show that house height did not greatly affect indoor comfort levels.

2.1.4 Interpretation

Raising huts from the ground reduces mosquito hut entry and makes them slightly cooler. Our findings support the construction of multi-story buildings for reducing malaria transmission in sub-Saharan Africa.

2.1.5 Funding

Pump-prime Funding, BOVA Network, Global Challenges Research Fund, United Kingdom

2.2 Introduction

The United Nations has projected that the population of sub-Saharan Africa will more than double between 2019 and 2050, and the region will become the world's most populated by 2062 [124]. Coincident with the increasing growth rate, there has been an unprecedented improvement in the housing stock in the region, with the proportion of improved houses increasing from 11 % in 2000 to 23 % in 2015 [85]. With an additional 1.05 billion people in sub-Saharan Africa in 2050 [124], there has never been a better time to improve the quality of housing in the region and make houses healthier.

In 2020, there were 602,000 deaths from malaria in the African region, representing 96 % of the global total[1]. It is particularly concerning that the decline in malaria cases has stalled in recent years and is increasing in some countries despite the massive deployment of insecticide treated nets (ITNs), indoor residual spraying (IRS) and prompt and effective treatment with antimalarials. It is generally recognized that supplementary measures are needed to further decrease malaria in the region. Since 79 % of malaria cases are transmitted when people are in bed [100], reducing mosquito house entry would contribute to malaria control.

There is growing evidence that the design of a house can affect greatly the force of malaria infection, especially in sub-Saharan Africa where the vectors are active indoors at night. A systematic review and meta-analysis showed that residents of modern homes had 42 % lower odds of malaria infection compared to traditional homes and a 54–65% lower incidence of clinical malaria. Similarly, a meta-analysis of 29 malaria surveys carried out in 21 sub-Saharan African countries between 2008 and 2015, found that modern housing was associated with a 9-14 % reduction in the odds of malaria infection compared with traditional housing, a level of protection comparable to ITNs. Modern houses are more likely to have closed eaves, the gap between the top of the wall and the over-hanging roof, and screened windows and doors, all modifications known to reduce the entry of malaria mosquitoes into houses [84]. Completely closing a building in the hot humid tropics, however, will reduce ventilation and increase the temperature of the house before midnight, particularly if the roof is metal [83,101]. Making a house hotter, will impede malaria control, since being too hot is the main reason people give for not sleeping under a mosquito net at night [3]. Therefore, the ideal house is one that keeps out malaria vectors, whilst keeping the occupants cool. In a review of the existing studies on house modification to prevent malaria [125] the authors established several limitations including that supporting evidence is based on entomological and observational studies rather than epidemiological ones, that this approach is likely to be a top-down one and that it will not benefit the population that needs it the most. It is important, however, to continue exploring innovative ways of vector control that could be tested in a larger scale in the future.

The study hypothesized that raising a house above the ground would reduce mosquito house entry and keep the house cool. Support for this hypothesis comes from several sources. Firstly, field studies in The Gambia showed that 80% of mosquitoes fly less than one metre from the ground [40,107]. Secondly, raised platforms [101,126,127], or even keeping the feet off the ground, can reduce biting by malaria mosquitoes [108,128]. Thirdly, a pilot study in Tanzania, showed that screened double-storey buildings had 96% fewer malaria mosquitoes compared to outdoors levels, whilst in screened single-storey buildings there were 77% less than outdoor levels [127]. The double-storey buildings were also 1.8 $^{\circ}$C cooler than unmodified single-storey buildings.

The first experimental study was carried out to determine whether raising the height of a house would reduce house entry of malaria mosquitoes and keep the house cooler at night in a rural part of The Gambia.

2.3 Methods

2.3.1 Study design

This was an experimental study with four identical huts, each one that could be moved up or down. All huts had badly-fitting doors, open eaves and no windows, to replicate houses common in the region. The height in which each hut was positioned changed weekly, following a replicated Latin rectangle design (Table 2.1). We had two primary objectives. Firstly, to determine whether mosquito house entry declined with increasing height and secondly, to determine whether an elevated hut would be cooler than one on the ground.

Table 2. 1 Replicated Latin rectangle design for experimental huts heights.

	Height of hut above ground (m)			
Session	Hut 1	Hut 2	Hut 3	Hut 4
1	2	0	3	1
2	1	3	0	2
3	0	1	2	3
4	3	2	1	0
5	2	1	0	3
6	3	0	1	2
7	1	3	2	0
8	0	2	3	1
9	2	0	3	1
10	1	3	0	2

2.3.2 Study area

The study took place on the edge of Wellingara village (N 13° 33·365', W 14° 55·461'), located in the Central River Region, The Gambia. This is an area of flat Sudanese savanna, located close to a large rice-cultivated area. The study took place in 2019 during the rainy season, from August 5th to October 17th, when numbers of *An. gambiae* are greatest [83].

2.3.3 Experimental huts

Four experimental huts were constructed, 10 m apart, along a straight line on the western edge of the village, closest to the large irrigated Jahally-Pacharr rice fields. The design of the huts is similar to single storey buildings in the area with doors on opposite sides, but they are smaller and constructed from lightweight material so they could be safely moved up and down (https://vimeo.com/413154392; password: upanddown2019). The huts were constructed from waterproof plywood mounted on a timber frame and had a corrugate steel roof (Figure 2.1). Each hut was 3.10 m by 3.10 m in area and the walls 2.20 m high. Each hut had two doors, 1.80 m high and 0.70 m wide, with 20 mm slits gaps on the top and bottom of each door, with one door facing the rice fields, and the other the village. The saddle roof was constructed from steel corrugate sheets mounted on a timber frame, with open eaves on the sides of the house with the doors (Figure 2.1). Each house was arranged with two beds located parallel to one another on opposite walls, on the sides without doors. The huts were fixed to a steel frame, which allowed the hut to be raised and lowered using pulley lifts (Yale lever hoist, VSIII 2000 Kg Manual Chainblock, Yale, UK). The hoists were anchored in a steel frame that was fixed at ground level by steel foot brackets cast into reinforced concrete foundations (1.65 m x 1.67 m x 0.50 m high).

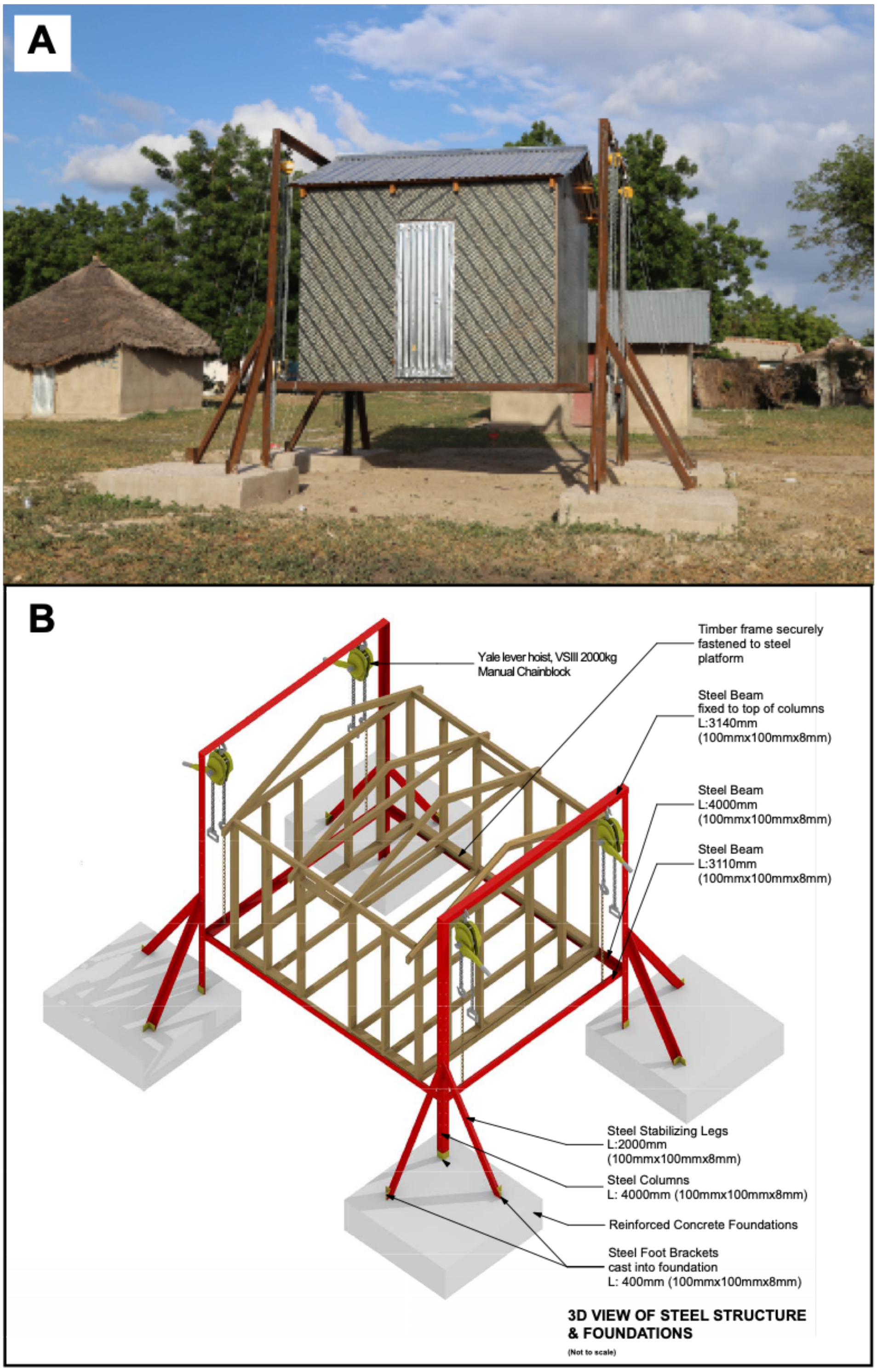

Figure 2. 1 Experimental hut.

A = constructed hut raised at 1 m and B = 3D technical drawing (B).

The study was explained to men in Mandinka, the local language, at a village meeting. Eight healthy men over 15 years old living in Wellingara village, provided signed-witnessed consent and were recruited for the study. Before the first experimental session, volunteers slept in the huts for one night to impregnate the huts with the smell of humans. Each night each pair of volunteers slept, with their heads closest to the rice fields, under separate insecticide-treated nets (Olyset Net, 1.30 m wide, 1.50 m high and 1.80 m in length, Sumitomo Chemicals, Japan) from 21.00 h to 07.00 h the following morning (Figure 2.2). Each pair of volunteers were rotated between huts each night so that at the end of each week, each pair had slept in each hut. Two field assistants were stationed throughout the nights to assist the volunteers with ladders if they needed to leave the hut during the night. Volunteers slept in the huts for four nights a week for ten weeks.

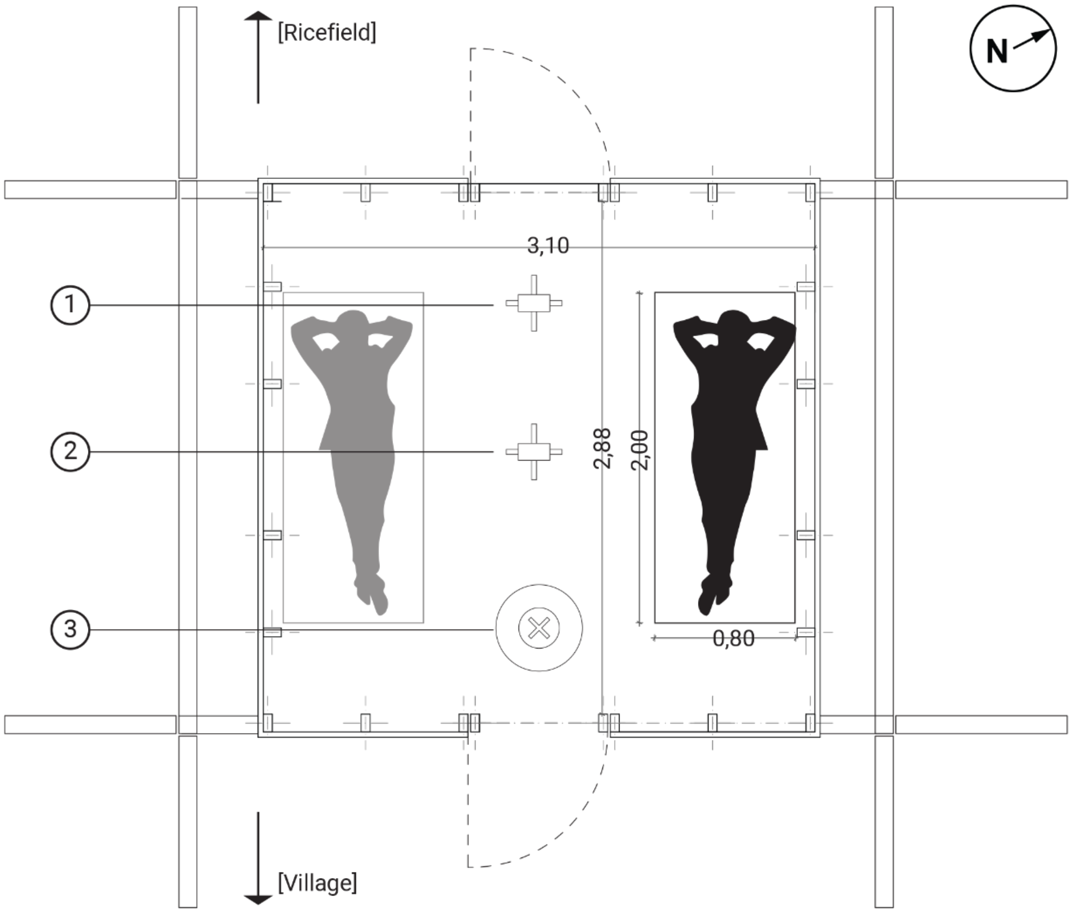

Figure 2. 2 Position sleepers and environmental loggers in experimental hut.
1 = carbon dioxide data logger, 2 = temperature data logger and 3 = CDC light trap.

2.3.4 Outcomes

The main entomological outcomes were mean number of *An. gambiae* s. l. and mean temperature of huts at different heights before and after midnight. Mosquitoes were collected using one light trap (Miniature light trap model 512, US Centers for Disease Control and Prevention, John W. Hock Ltd, Gainsville, USA) in each house, located with the light bulb 1 m above the floor and between the feet of the two beds. Light traps were operated from 21.00 h to 07.00 h the following morning. Every night, the field assistants conducted two supervisory visits, at 00.00 h and 06.00 h, to make sure the men were in the huts, assess bed-net use and make sure the light traps were working properly. After collection, mosquitoes were placed in a -20 °C freezer until dead. Mosquitoes were identified using standard morphological identification keys [16,129], and members of the *An. gambiae* complex identified using polymerase chain reaction [130–132].

Indoor temperature and relative humidity were measured in each hut every 30 min using a data logger (TGU 4500, Tinytag, UK) positioned in the centre of the room, 1 m above the floor. Carbon dioxide was recorded every 30 seconds with data loggers (1% CO2 + Rh/T Data Logger GasLab, Florida, USA) located between the beds near the head of the bed, 1 m above the floor (Figure 2.2). Outdoor temperature, relative humidity, wind speed, wind direction and precipitation were recorded with an automatic weather station (MiniMet, Skye Instruments, Llandrindod Wells, UK) every 30 minutes, located 10 m from the centre of the huts' line.

After the collections ended, all sleepers participated in a focus group discussion. During the discussion, the men discussed their experiences of sleeping in the houses and explored their willingness to live in a house raised from the ground. The discussion was conducted in Mandinka. The focus group and translation to English were audio recorded and transcribed into English for analysis.

2.3.5 Statistical analysis

For the entomological analysis we used IBM SPSS Statistics 20 and Stata version 24. We estimated the sample size with a simulation based in a study conducted in the same area in 2017 [83]. In this study, the mean number of *An. gambiae* s.l. collected indoors over a 25-night study was 6.4 mosquitoes per house per night (Standard deviation = 7.1). The study was powered to detect an intervention that reduces the number of mosquitoes found indoors by at least 75 % at the 5 % level of significance and 90 % power. In the simulation the 4 x 4 Latin square was repeated from 3 to 10 times (i.e. 12 to 40 nights). The simulation showed that eight, 4 x 4 Latin squares would provide sufficient power to detect a 75% reduction in mosquito house entry (i.e. 32 nights of collections). In the study we extended this period for two more weeks, because of low mosquito catches in the first two weeks.

Entomological data was analysed in two phases. First, data was analysed using mean indoor mosquito numbers in each house typology. These unadjusted results are presented as bar charts in the findings sections. Second, I used generalised estimating equations (GEE) using a negative binomial model with a log link function for mosquito count to assess the effect of hut height on mosquito house entry. This analysis was adjusted for hut height, hut position, sleeper pair and number of night as fixed effects in the model. The mean ratio is the expression of the difference of indoor mosquito density in reference to the control hut while the protective factor of the hut against mosquito entry (1-mean ratio x 100) is the expression of the effect of the intervention. Similarly indoor climate results were adjusted for the same effects and analysed using a normal distribution with identity link for temperature and carbon dioxide, since they were continuous variables normally distributed and the proportion in relation to the control house is expressed as "difference from control house". A GEE model assesses the effect of one factor on a longitudinal study and is appropriate for adjusting for repeat measures in the same house or hut [133]. This method has been used in clinical trials and biomedical studies primarily. We used polar plots to depict the direction and strength of the wind during the day and night. To examine the relationship between carbon dioxide concentration and covariates, we used a linear regression.

The study was approved by the Gambia Government and Medical Research Council's joint ethics committee (October 17, 2018) and the Department of Biosciences ethics committee, Durham University, UK (January 11, 2019).

2.4 Findings

2.4.1 Entomology

A total of 17,432 female mosquitoes were collected in the experimental huts over 40 nights. Of these, 2,080 (11.9 %) were *An. gambiae* s.l., 13,321 (76.4 %) *Mansonia* spp., 1,823 (10.5 %) *Culex quinquefasciatus* and the rest other anophelines, *Aedes* *aegypti* and *Culex thalassius*. Mosquitoes identified as *An. gambiae* s.l. were identified with PCR analysis as *An. arabiensis* (29.4%), *An. coluzzii* (68.0%) and *An. gambiae* s.s. (2.6%). Undajusted analysis showed that fewer numbers of *An. gambiae* s.l., *Mansonia* spp. and all mosquitoes entered huts as the height of the hut was raised from the ground (Figure 2.3). The number of culicine mosquitoes entering houses, however, was not affected by the height of the house.

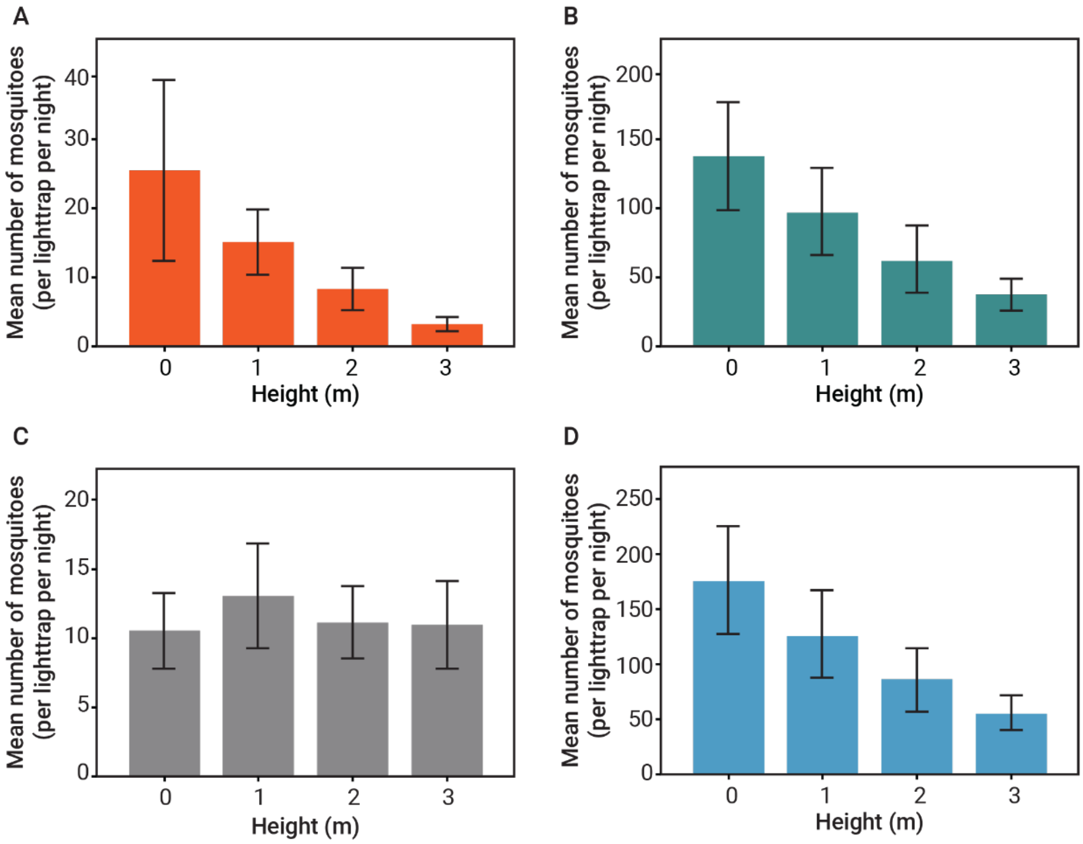

Figure 2. 3 Unadjusted mean numbers of female mosquito hut entry in experimental huts at different heights.
A= *An. gambiae*, B= *Mansonia* spp., C= *Culex quinquefasciatus*, D= all mosquitoes. Error bars are 95% confidence intervals. NB scales differ for each mosquito group

The adjusted analysis showed that numbers of female *An. gambiae* entering the huts declined with increasing hut height (protective efficacy), declining by 41% (95% CI 24 to 53%) at 1 m, 68 % (95% CI 60 to 74%) at 2 m and 84 % (95% CI 77 to 89 %) at 3 m, compared to the hut at 0 m (Table 2.2). Similar reductions were seen with *Mansonia* spp., but not with culicines, where the number of hut entering mosquitoes was similar in all raised huts compared to the hut on the ground. Overall, numbers of mosquitoes of all species entering huts decreased with increasing height; from 33% at 1 m, 57% at 2 m and 69% at 3 m.

Table 2. 2 Total female mosquitoes collected in experimental huts at different heights and adjusted analysis.

Generalized linear modelling results, adjusted for hut position, sleeper pair and number of night. Figures in parentheses are 95% confidence intervals.

Height of hut (m)	No. collected	Dif. from control hut (95% CIs)	Protective efficacy (95% CIs)	p value
Female *Anopheles gambiae*				
0	1015	Reference	..	..
1	601	0.60 (0.47 to 0.76)	- 41 % (24 to 53)	< 0.001
2	333	0.32 (0.26 to 0.40)	- 68 % (60 to 74)	< 0.001
3	131	0.16 (0.12 to 0.23)	- 84 % (77 to 89)	< 0.001
Female *Mansonia* spp.				
0	5475	Reference	..	..
1	3880	0.62 (0.50 to 0.77)	- 38 % (23 to 50)	< 0.001
2	2486	0.35 (0.29 to 0.43)	- 65 % (57 to 71)	< 0.001
3	1471	0.24 (0.18 to 0.30)	- 77 % (70 to 82)	< 0.001
Female *Culex* spp.				
0	420	Reference	..	..
1	522	1.11 (0.79 to 1.58)	+ 11 % (-58 to 21)	0.546
2	444	1.13 (0.95 to 1.35)	+ 13 % (-35 to 5)	0.168
3	437	1.00 (0.86 to 1.15)	0 % (-15 to 14)	0.974
All mosquitoes				
0	6998	Reference	..	..
1	5069	0.67 (0.43 to 1.06)	- 33 % (-6 to 57)	0.087
2	3326	0.43 (0.34 to 0.55)	- 57 % (45 to 66)	< 0.001
3	2140	0.31 (0.26 to 0.37)	- 69 % (63 to 74)	< 0.001

2.4.2 Environmental measurements

Indoor temperatures declined from 29.0 °C at 21.00 h to 25.5 °C at 07.00 h, but were always about 2 °C warmer than outdoors (Figure 2.4). Although by univariate analysis there were no significant differences between indoor temperatures in the different huts (Table 2.3), figure 2.4 shows a trend for decreasing temperature when the huts are higher off the ground. Adjsuted analysis showed that indoor temperature variation was of borderline significance only when comparing the hut at 3 m with the house on the ground during the second part of the night. During this period the hut at 3 m was 18% (95% CI -0.01 to 24) cooler than the control hut (Table 2.3). No differences in relative humidity were found between huts (Table 2.3).

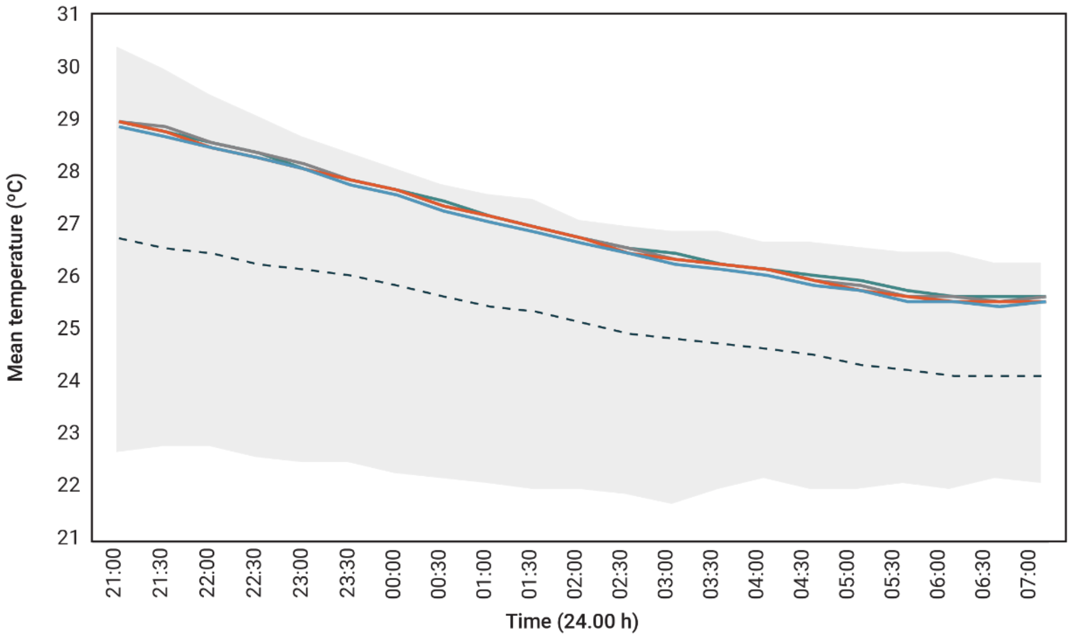

Figure 2. 4 Unadjusted mean temperature from 21.00 h to 07.00 h.
Gray area = minimum and maximum outdoor temperature levels, Turquoise line = hut at 0 m, grey line = hut at 1m, orange line = hut at 2 m, light blue line = hut at 3 m and dashed black line = outside measurements.

Table 2. 3 Mean temperature and relative humidity recorded in experimental huts at different heights and adjusted analysis.
Linear modelling results, adjusted for hut position, sleeper pair & number of night. Figures in parentheses are 95% confidence intervals.

	Average temperature from 21.00 h to 23.30 h			Average temperature from 00.00 h to 07.00 h		
	Average (ºC)	Difference from control hut	p value	Average (ºC)	Difference from control hut	p value
Outdoors	26.5 (26.3 to 26.7)	..	..	24.8 (24.7 to 24.9)	..	..
Hut at 0m.	28.4 (28.1 to 28.6)	Reference	..	26.4 (26.2 to 26.5)	Reference	..
Hut at 1m.	28.4 (28.1 to 28.7)	1.05 (0.99 to 1.12)	0.103	26.6 (26.4 to 26.8)	1.11 (0.90 to 1.37)	0.328
Hut at 2m.	28.3 (28.1 to 28.6)	0.98 (0.93 to 1.03)	0.423	26.3 (26.2 to 26.4)	0.95 (0.83 to 1.10)	0.507
Hut at 3m.	28.3 (28.0 to 28.5)	0.97 (0.91 to 1.02)	0.211	26.2 (26.1 to 26.4)	0.88 (0.76 to 1.01)	0.067
	Average relative humitidy from 21.00 h to 23.30 h			Average relative humidity from 00.00 h to 07.00 h		
	Average (%)	Difference from control hut	p value	Average (%)	Difference from control hut	p value
Outdoors	90.53 (89.74 to 91.33)	..	..	94.27 (93.54 to 94.99)	..	..
Hut at 0m.	77.05 (75.44 to 78.66)	Reference	..	82.04 (81.15 to 82.93)	Reference	..
Hut at 1m.	76.45 (74.83 to 78.07)	0.43 (0.31 to 0.61)	< 0.001	82.17 (81.20 to 83.14)	0.62 (0.42 to 0.91)	0.016
Hut at 2m.	76.72 (75.01 to 78.43)	0.43 (0.34 to 0.54)	< 0.001	82.25 (81.28 to 83.21)	0.71 (0.36 to 1.40)	0.321
Hut at 3m.	77.25 (75.62 to 78.88)	0.81 (0.44 to 1.51)	0.505	82.89 (81.89 to 83.90)	1.75 (0.98 to 3.12)	0.061

Although there is considerable nightly variation in the pattern of carbon dioxide seen in each hut, the mean values provide consistent patterns and show clear trends between huts (Figure 2.5). Carbon dioxide levels rose sharply from when men entered the huts to a maximum value 30 minutes later. Thereafter levels gradually declined during the night before rising sharply around 05.00 h to a second, smaller peak at 07.00 h, when the men left the huts. There was a decreasing trend in the concentration of carbon dioxide with increasing height. This was confirmed in the adjusted analysis that showed that carbon dioxide concentrations were less when the huts were raised off the ground, compared with the hut at 0 m, both before and after midnight (Table 2.4). An analysis, adjusting for night, sleeper pair and geographical position, showed that before midnight there was a 24.8 % decline in carbon dioxide at 1 m, 39.8 % at 2 m (Rate ratio, RR = 0.60, 95% 0.51 to 0.72) and 44.8 % at 3 m (RR = 0.55, 95% CI = 0.46 to 0.66) compared to the hut on the ground. Whilst, after midnight, there was a 19.7 % decline in carbon dioxide at 1 m, 25.4 % at 2 m (Rate ratio, RR = 0.75, 95% 0.65 to 0.86) and 38.4 % at 3 m (RR = 0.62, 95% CI = 0. 54 to 0.71) compared to the hut on the ground.

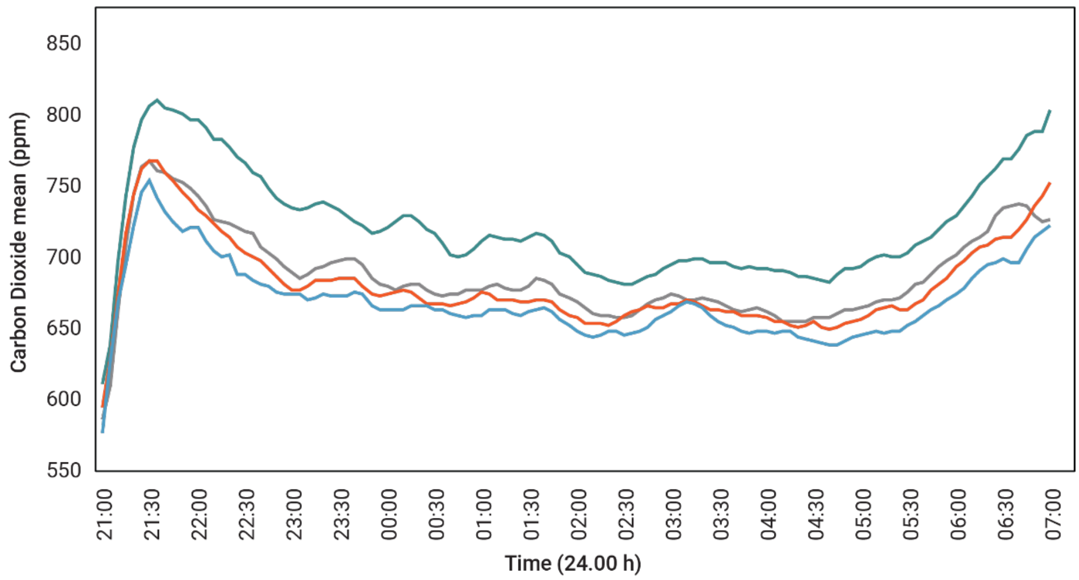

Figure 2. 5 Unadjusted mean carbon dioxide concentration from 21.00 h to 07.00 h. Turquoise line = hut at 0 m, grey line = hut at 1m, orange line = hut at 2 m, light blue line = hut at 3 m and dashed black line = body temperature (Y axis).

Table 2. 4 Mean carbon dioxide recorded in experimental huts at different heights and adjusted analysis.

Linear modelling results, adjusted for hut position, sleeper pair and number of night. Figures in parentheses are 95% confidence intervals.

	Average carbon dioxide from 21.00 h to 23.30 h			Average carbon dioxide from 00.00 h to 07.00 h		
	Average (ppm)	Difference from control hut	p value	Average (ppm)	Difference from control hut	p value
Hut at 0m.	760 (710 to 800)	Reference	..	710 (680 to 750)	Reference	..
Hut at 1m.	710 (680 to 740)	75.2 (60.6 to 93.4)	0.010	680 (650 to 710)	80.3 (70.1 to 92.0)	0.002
Hut at 2m.	710 (680 to 740)	60.2 (50.7 to 71.5)	< 0.001	670 (640 to 700)	74.6 (64.9 to 85.9)	< 0.001
Hut at 3m.	690 (660 to 730)	55.2 (45.9 to 66.4)	< 0.001	660 (630 to 700)	61.6 (53.9 to 70.5)	< 0.001

2.4.3 Focus group discussions

Sleepers preferred to sleep in the hut at ground level and the hut at 3 m high. When asked the reasons for their choice they mentioned that the higher hut was cooler and had fewer mosquitoes disturbing them during the night. The sleepers also said they did notice a change in temperature throughout the night.

"*I am very happy whenever I am going to level three* [3 m hut]. *I am very, very happy*"
"*Initially [it] is very, very hot inside, before twelve [at night]. By twelve it starts to get cold.*"

Sleepers said that they would live in a house raised from the ground if it was made of solid [mud block] materials like traditional houses and had a fixed stair to access the house if it was to be permanent.

" [The houses would be more useful] *if the houses are solid, like the way the ones* [built] *on the ground. We would prefer that.*"
"*As I said, I prefer the stair that is fixed to the house. I prefer if all the stairs would be in that form. It would be much more appreciated.*"

2.5 Discussion

The number of female *An. gambiae* mosquitoes collected in the huts declined with increasing height, roughly decreasing by half for every one meter increase in height. A hut 3 m above the ground had 84 % fewer mosquitoes than a similar hut on the ground. If this reduction correlates to a similar reduction in malaria transmission, it would be roughly equivalent to that of an insecticide-treated net that can reduce malaria transmission by 70 %. Similar reductions occurred in the numbers of *Mansonia* spp. as the height of a house was raised, with the hut at 3 m having 76.5% less mosquitoes than the hut on the ground. In marked contrast, the number of culicines entering the experimental huts was similar at all heights.

The findings of this study are supported by a series of studies that measured the height at which mosquitoes fly, conducted in the same study area [107] and two other sites in The Gambia carried out in the 1960s and 70s [40,134]. Mosquitoes were collected at different heights using suction traps mounted on scaffolding, 80 % of the total catch of mosquitoes was collected between the ground level and 1.00 m [134]. They differentiated between low-flying mosquitoes, including *Anopheles* spp. and *Mansonia* spp., *Aedes punctothoracis* and higher flying mosquitoes that could be collected at 3.5 to 4 m, which included *Cx. neavei* and *Cx. weschei*. Interestingly, although *An. gambiae* s.l. and *Mansonia* spp. fly close to the ground, when tracking odours from a house they fly up and enter a house through a gap 1.70 m high, whilst mosquitoes like *Aedes spp.*, *An. pharoensis*, *Cx. poicilipes* and *Cx. thalassius*, will not [40]. In another study, conducted in the same location as the one in this chapter, 6 m high circular netting fences surrounding a radius of 65 m showed that that *An. gambiae* and *Mansonia* spp, moved up and over the fence [107]. This study raises the question of whether house height is protective if raised houses are closed underneath by a netting fence or solid walls. A study in Tanzania, however, found that mosquito entry decreased in two-storey houses compared with traditional ones [127]. Mosquito catches was reduced by 96% (95% CI 92 to 98) in the two-storey house and by 43% (95% CI 36 to 50) in modified traditional houses, compared with unmodified control houses. Similarly, a recent study in Kenya found that thatched roofed and mud wall houses raised on stilts had 81 % fewer malaria vectors indoors than those located on the ground built with the same materials [135].

In this study, indoor temperature differences were only significant when one compared the hut at ground level with the house at 3 m during the second part of the experimental night. This difference might be because elevated houses are more exposed to air currents that are not blocked by the single-storey houses in the adjacent village. This finding is supported by a study which found that two-storey houses were 2.3 ºC (95% CI 2.2 to 2.4) cooler than single-storey houses [127]. It is presumed that atmospheric decrease in air temperature with increasing altitude does not affect the huts since they are too close to the ground to experience that change [136]. Additionally, indoor temperature declined rapidly after midnight, and study participants mentioned that the huts "started to get cold by 12 [midnight]" during early hours in the morning close to the end of the study and the start of the cold season in The Gambia. This rapid decrease in temperature was attributed to the fact that none of the huts were in direct contact with the ground to receive heat irradiated from the ground [136] and that houses were built with materials with a high capacity to loose heat, like metal corrugated roofs and plywood walls. Temperature outside was influenced by wind speed and direction (Figure 2.6), which came from the village rather than from the rice field and might have been reduced by adjacent villages houses.

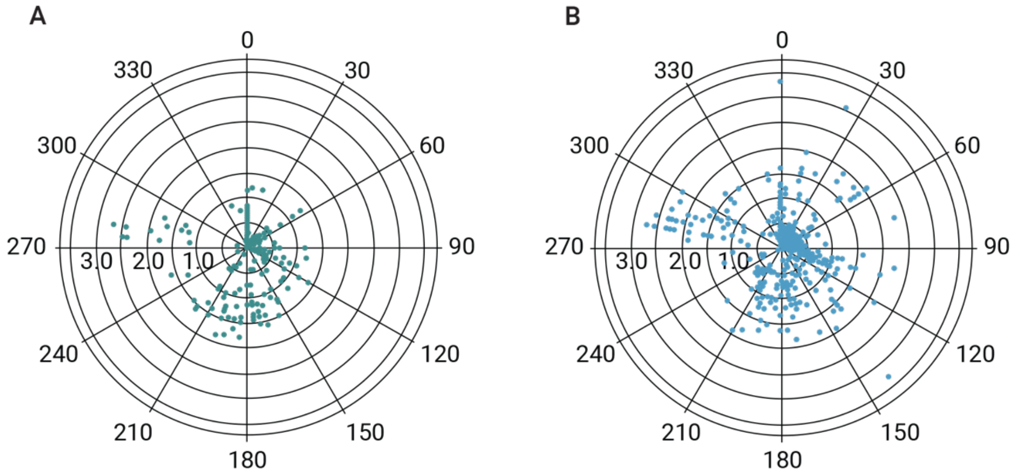

Figure 2. 6 Wind direction and speed during the experimental nights.
Where A = first part of the night (21.00 h to 23.30 h) and B = second part of the night (00.00 h to 07.00 h).

Carbon dioxide levels rose rapidly after the men entered the huts and then slowly declined through the night until it started to rise at 05.00 h to a second peak at 07.00 h, when the men left the huts. Both peaks were associated with the increased physical activities, the first, chatting and preparing to go to bed, and the second, praying and getting ready to leave the huts in the morning. The prolonged decline in carbon dioxide during the night is associated with a decline in physical activity and sleep, with an associated reduction in respiratory rate and increased carbon dioxide concentrations in the body[121]. There was a progressive decrease in carbon dioxide levels as the height of the hut increased, due to a combination of lower indoor temperatures and stronger winds at higher elevations [136]. Since carbon dioxide and other volatiles produced by humans are strong attractants for blood-questing mosquitoes[37], the lower concentrations experienced in elevated huts is likely to contribute to the decline in mosquitoes seen with increasing hut height. The changing pattern of carbon dioxide in our experiment was roughly coincident with mean core body temperatures during the night[137,138], suggesting that levels of carbon dioxide change as a direct result of changes in circadian activity.

During the focus group, participants discussed the absence of mosquitoes bothering them as one of the main qualities of the experimental huts. In general, participants preferred to sleep in the huts located at 3 m and at ground level. It may be that their preference for the experimental hut at ground level was linked with the common tradition of living in single-storey houses and not with comfort levels. This assumption was corroborated with the preference regarding solid materials, mentioned during the focus group discussion. Hence there is a perceived norm for local houses to be built on the ground and of solid materials.

In sub-Saharan Africa most rural houses are single-storey buildings, constructed on the ground [139]. Nevertheless, there are numerous examples of indigenous structures built raised off the ground for three main reasons. Firstly, grain stores are commonly built off the ground to prevent infestations with rodents, such as raised Kongo Granaries in Angola [140] and multi-storey Dogon granaries in Mali [98]. Secondly, raised houses are built for avoiding damp or flooded ground. For example, houses built by the Lafofa people in southern Sudan, are designed in a ring and raised to avoid dampness [98]. In Benin, the lake village of Ganvie, the "Venice of Africa", a UNESCO World Heritage site, is built on stilts [141,142]. And in Nigeria, Makoko is one of Lagos' largest informal settlements [143]. Various coastal or riverside communities have been building houses on stilts for decades as prevention for flooding [98] or as a protection strategy [144]. Contemporary examples of elevated houses can be found in Sao Tome and Ghana (Charlwood, D., personal communication). Thirdly, two-storey houses or higher are built because of a shortage of land, in order to increase living space (Figure 2.7). These structures are part of the urban landscape of many African cities and towns, and alongside busy roads where shops are frequently two-storey structures. As land becomes in short supply, the likelihood of building multi-storey buildings will increase.

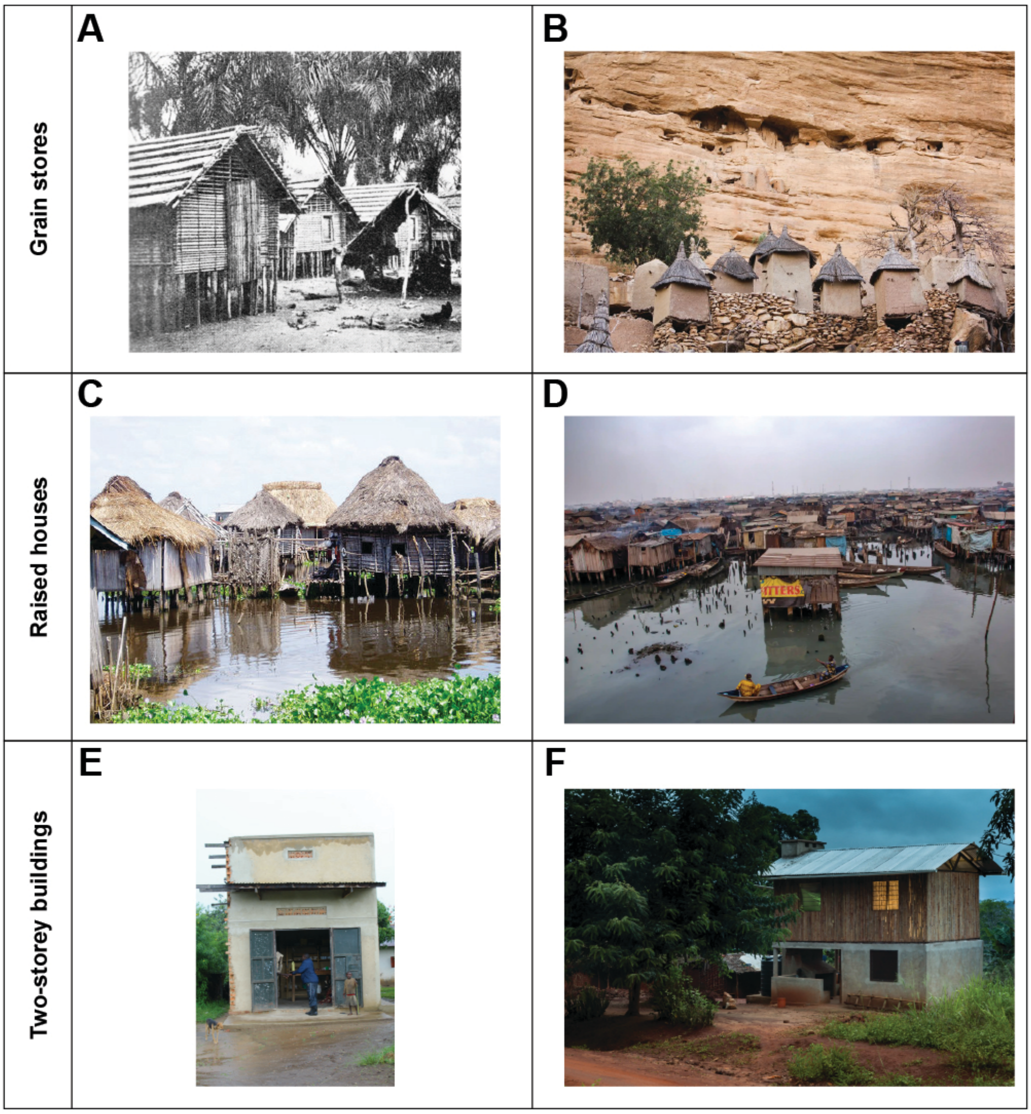

Figure 2. 7 Raised and two-storey constructions in Africa.
A = Kongo Granaries in Angola, 1910 (Knudsen, J., Presentation); B = Dogon Granaries in Mali, 2016 (Hamaji Magazine); C = Ganvie in Benin, 2018 (Scribol Magazine); D = Makoko in Nigeria, 2016 (The Guardian); E =Two-storey house with store in the ground floor in The Gambia (Lindsay, S., Personal collection); F =Double-storey bamboo prototype house in Tanzania (von Seidlein, L. *et al.* Affordable house designs to improve health in rural Africa: a field study from northeastern Tanzania.)

There are several limitations to this study. Firstly, the experimental huts were smaller than traditional single-room houses and made with marine plywood walls instead of mud or cement blocks. This made the huts hotter during the day and probably cooler at night compared with traditional houses and the movement of carbon dioxide in these buildings will differ from typical houses. Secondly, adults go to bed later in the night, around midnight [64], when it is cooler, than in this study, where they go to bed at 21.00 h. Thirdly, single room houses are common in Fula and Wolof communities, but in Mandinka villages line houses are common, consisting of multiple rooms, side by side[101]. Fourthly, the house at 0 m is not resting on the ground, since there is a 0.40 m space between the ground and building. Consequently, this house is cooler at night, than one fixed to the ground as it does not absorb the heat irradiated by the ground [136]. Lastly, it is unknown whether closing the space under an elevated house will result in mosquitoes rising up the sides of the building and entering the dwelling room in higher numbers than a similar building that is open underneath.

The findings of this chapter show that the number of malaria mosquitoes entering a house declines with increasing height of the hut. This behaviour presumably results from the habit of most mosquitoes flying less than one metre above the ground and lower production of carbon dioxide and other attractants in the cooler elevated houses. Essentially, mosquitoes are less likely to feed on a person sleeping in an elevated house than one on the ground. At 3 m, this reduction in indoor entry is equivalent to the protection afforded by an insecticide-treated bed-net. Raising houses off the ground is not an evolutionary proof intervention, and over time, mosquitoes may adapt and feed higher off the ground than before. Nonetheless, we recommend elevating houses off the ground since they are likely to reduce mosquito biting and keep the occupants cooler at night[84], and therefore more likely to use an insecticide-treated net. This research is likely to be relevant to many hot and humid parts of sub-Saharan Africa geographical contexts where *An. gambiae* is the major vector of malaria and places where high temperatures prevent the use of bed-nets. Architectural interventions, combined with protective measures against vectors, such as insecticide-treated nets, indoor residual spraying and eaves tubes increase the level of indoor protection against vectors. In the future new methods of protection such as insecticide-treated curtains and insecticide-treated eave ribbons may provide additional protection. Raising houses off the ground is likely to reduce mosquito house entry and keep the house cooler, and merits further research to explore the epidemiological impact of elevated houses, their acceptability within the possible users and to evaluate the capacity of the existing infrastructure to adapt to raised houses.

Chapter 3. The effect of physical barriers under a raised house on mosquito entry: an experimental study in rural Gambia

3.1 Abstract

3.1.1 Background

Anopheles gambiae, the major malaria mosquito in sub-Saharan Africa, feed largely indoors at night. Raising a house off the ground with no barriers underneath reduces mosquito-house entry. Here we test whether walling off the space under an elevated hut affects mosquito-hut entry.

3.1.2 Methods

Four inhabited experimental huts, each of which could be moved up and down, were used in rural Gambia. Nightly collections of mosquitoes were made using light traps and temperature and carbon dioxide monitored indoors and outdoors using loggers. Each night, a reference hut was kept at ground level and three huts raised 2 m above the ground; with the space under the hut left open, walled with air-permeable walls or solid walls. Treatments were rotated every four nights using a randomised block design. The experiment was conducted for 32 nights. Primary measurements were mosquito numbers and indoor temperature in each hut.

3.1.3 Findings

A total of 1,259 female *Anopheles gambiae* were collected in the hut at ground level, 655 in the hut with an open ground floor, 981 in the hut with air-permeable walls underneath and 873 in the hut with solid walls underneath. Multivariate analysis, adjusting for confounders, showed that a raised hut open underneath had 53% fewer mosquitoes (95%CIs=47-58), those with air-permeable walls underneath 24% fewer (95%CI=9-36) and huts with solid walls underneath 31% fewer (95% CI= 24-37) compared with a hut on the ground. Similar results were found for *Mansonia* spp. and total number of female mosquitoes, but not for *Culex* mosquitoes where hut entry was unaffected by height or barriers. Indoor temperature and carbon dioxide levels were similar in all huts.

3.1.4 Interpretation

Raising a house from the ground reduces the entry of *An. gambiae* and *Mansonia* mosquitoes, but not *Culex* species. The protective effect of height is reduced if the space underneath the hut is walled off.

3.1.5. Funding

Pump-prime Funding, BOVA Network, Global Challenges Research Fund, United Kingdom

3.2 Introduction

By 2050, the population of sub-Saharan Africa is projected to increase by 1.05 billion, an increase roughly representing the present population of India or China, becoming the most populated region on the world around 2060 [124]. Most of the projected rise in population will occur in secondary cities and towns, with urban areas growing in population by 87 % [124]. Whilst settlements will expand in area, land scarcity and rising land prices require new solutions to provide affordable high-density homes for the increasing population. Inevitably, this means constructing vertical housing [145,146].

Malaria remains a major public health problem in the African region with 228 million cases in 2020 [1]. About 79 % of these cases were infected with malaria parasites indoors at night [100], highlighting the importance of protecting people from malaria mosquitoes in their homes. Since 2000, the major interventions used for protecting people indoors in the region have been insecticide-treated nets (ITNs), and, to a lesser extent, indoor residual spraying [1]. Although major reductions in malaria have been recorded since the turn of the century, today malaria control has stalled, with the number of cases increasing in some countries [15,63]. Complementary strategies are therefore needed to prevent a resurgence of malaria, particularly during the COVID-19 pandemic where malaria control is no longer the public health priority and service disruptions are common [1].

Improved housing could be used as a complementary strategy to reduce the force of malaria infection [84]. Changes to the structure of a house can directly and indirectly reduce malaria mosquito house entry. Mosquito screens on doors and windows act as physical barriers to mosquito ingress [84] and, by increasing ventilation, reduces the number of mosquitoes that can locate entry points in a house [69,83]. Good ventilation reduces the concentration of carbon dioxide indoors, an important gas used by malaria mosquitoes for locating a host [37]. Incorporating two screened windows into a single-roomed house reduces the entry of *Anopheles gambiae*, the principal African malaria vector, by 79 % [83]. Improved ventilation can also have the additional beneficial effect of cooling the house at night, making it more likely that people will sleep under an ITN, since having a 'hot house' is one of the major reasons why people will not use a net at night [3].

Recently we have shown that raising experimental huts off the ground reduces the number of malaria mosquitoes entering the huts [147], with huts at 2 m above the ground having 68 % fewer mosquitoes than those on the ground. Since *An. gambiae* are low-flying mosquitoes, with most flying no more than one metre above the ground [40,107], we hypothesise that these mosquitoes find it difficult to locate the carbon dioxide, and probably other attractants, emanating from the raised huts. In these experiments the huts were supported by four columns at each corner, with no walls under the huts. In the real-world, many houses constructed off the ground have the ground floor walled to create an extra room or to store objects and food. In the 1970s, Gillies and Wilkes, in the same study location as ours, showed that *An. gambiae* can fly over a six metre high fence [107], suggesting that the protection resulting from raising a house off the ground would be reduced or nullified if there were physical barriers under the hut, perhaps causing low-flying mosquitoes to fly upwards, increasing the numbers entering the hut.

This experiment used four experimental huts (Figure 3.1) to measure house entry of *An. gambiae* s.l.; three huts were raised 2 m above the ground, close to the normal height of the floor of a second storey building in the neighbouring villages, and one at ground level served as the reference. There were two primary objectives, to: (1) determine whether mosquito-hut entry increased when the space directly beneath the hut was enclosed with different types of walls and (2) find out whether these alterations affected indoor temperature and carbon dioxide levels in elevated huts.

Figure 3. 1 Experimental huts.
A = raised hut with air-permeable walls underneath, B = raised hut with free ground storey, C = hut at ground level (control) and D = raised hut with solid walls underneath.

3.3 Methods

3.3.1 Study design

This experiment was designed primarily to determine whether adding solid or air-permeable walls under an elevated hut affected mosquito-hut entry and indoor temperature. Briefly, four identical experimental huts were constructed, each of which could move up and down. Three were fixed at 2 m above the ground and one kept at ground level. Of the three elevated huts, one had no barriers under the hut, one had air-permeable walls and one had solid walls fixed directly underneath the hut (Figure 3.2). Entry of mosquitoes into each hut was only possible through narrow gaps at the top and bottom of both doors, to replicate badly-fitting doors, common in the region. Treatments were changed every four nights, following a replicated Latin rectangle design (Table 3.1).

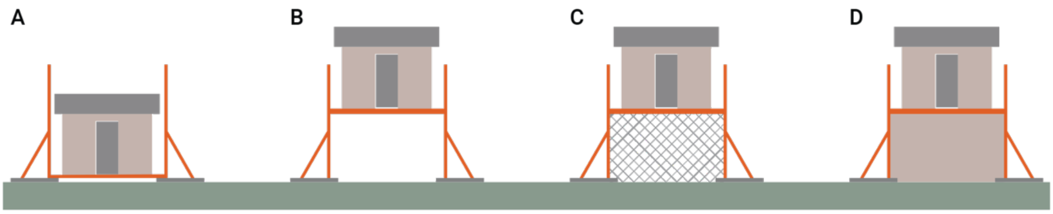

Figure 3. 2 Hut typologies used in the experiment.
A = hut at ground level (control), B = raised hut at 2 m with free ground storey, C = raised hut at 2 m with air-permeable walls underneath and D = raised hut at 2 m with solid walls underneath.

Table 3. 1 Replicated Latin rectangle design for experimental huts heights and ground floor treatment.
A = hut at ground level (control), B = raised hut at 2 m with free ground storey, C = raised hut at 2 m with air-permeable walls underneath and D = raised hut at 2 m with solid walls underneath

	Experimental hut typology			
Session	Hut 1	Hut 2	Hut 3	Hut 4
1	D	B	A	C
2	A	C	D	B
3	C	D	B	A
4	B	A	C	D
5	C	A	B	D
6	D	B	C	A
7	B	D	A	C
8	A	C	D	B
9	D	B	A	C
10	A	C	D	B

.

3.3.2 Study area

The study took place in Wellingara village (N 13° 33”365’, W 14° 55”461’), Central River Region, The Gambia. The study site was located on the edge of the village close to a large area of irrigated rice. The study took place during the rainy season 2021, from August 23rd to October 4th, when *An. gambiae* s.l. are common [147].

3.3.3 Experimental huts

As described in the previous chapter, four experimental huts were built, 10 m apart, along a straight line on the western edge of the village and close to an irrigated rice field. The huts were designed to resemble single-room houses common in rural Gambia, although they were smaller and constructed from lightweight materials to make it easier and safer to move them up and down. Each hut was 3.1 m wide on each side and 2.2 m high with two doors on opposite sides (east and west) and no windows. The only mosquito entry points were through 20 mm gaps above and below each door. For this study, the floor of each hut was positioned at two heights, the reference hut at 0 m and the comparator huts at 2 m. Each hut had two bamboo beds positioned next to the walls in an east-west direction, leaving a clear space between the doors. Each raised hut had a fixed wooden staircase on the eastern door, away from the rice field, the major source of mosquitoes.

Each experimental session, the huts were arranged into four typologies: (1) the reference hut on the ground, and three huts raised 2 m above the ground, with (2) open space underneath the hut, (3) air-permeable walls on the ground floor and (4) solid walls on the ground floor. The air-permeable enclosure was constructed using untreated fly screen walls (white plastic, 708 x 630 holes per sq m, Faura, San Isidro, Spain) to surround the ground storey (the space immediately beneath the hut). The solid enclosure was made from 12 mm thick plywood boards. The experiment was conducted for nine sessions of four nights each.

3.3.4 Human subjects

A village meeting was organized to explain the study to the Alkalo (village leader) and the village elders and to request their approval for the study. Following their approval, another meeting was organized and conducted with the villagers. Both meetings were conducted in Mandinka, the local language. Eight healthy men over 18 years old living in Wellingara village, provided signed-witnessed consent and were recruited to the study. Participants slept in the huts for a block of four nights, for nine sessions. i.e. 36 nights. Each night, each pair of men slept in each hut under individual ITNs (Olyset Net, 1.3 m wide, 1.5 m high and 1.8 m in length, Sumitomo Chemicals, Japan), from 21.00 h to 07.00 h the following morning (Figure 3.3) with their heads pointing west, towards the rice fields. Each pair of sleepers were rotated between huts each night so that at the end of each session's block, each pair had slept in each hut. Two field assistants were stationed on site each night in a separate room to supervise the study subjects during the night and to record study data.

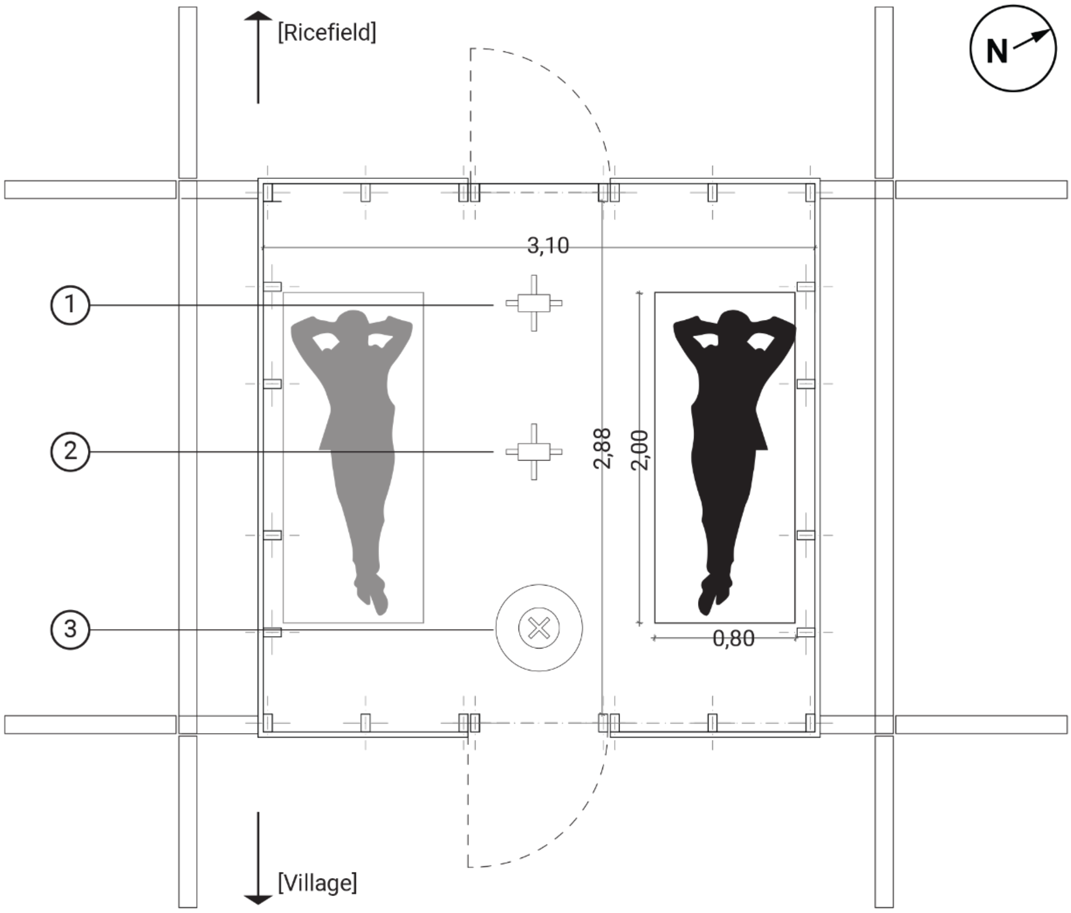

Figure 3. 3 Position of sleepers and environmental loggers in experimental hut.
A = carbon dioxide data logger, B = temperature data logger and C = CDC light trap.

3.3.5 Outcomes

The main entomological outcome was the mean number of female *An. gambiae* s.l. collected in light traps and the main environmental outcomes were mean temperature of huts and mean indoor carbon dioxide levels before midnight. Primary mosquito collection was done using one light trap (CDC-Centers for Disease Control and Prevention, Miniature light trap model 512, US John W. Hock Ltd, Gainsville, USA) per hut, which was operated when the men were in the huts, from 21.00 h to 07.00 h the following morning. Each light trap was located in between the feet end of the two beds, with the light 1 m above the floor. Secondary mosquito collection was performed every morning, using a Prokopack aspirator (Model 1419, John W. Hock Ltd, Gainsville, USA) for 10 min in each hut. Every experimental night, the field assistants conducted two supervisory visits, at 00.00 h and 06.00 h, to ensure that men were in the huts, light traps were working properly and to assess bed-net use. Every morning, collected mosquitoes were placed in a -

20 °C freezer until dead. Mosquitoes were identified using standard morphological identification keys [16,129], and a selection of female *An. gambiae* identified to species by PCR analysis [130–132].

Environmental conditions were recorded from 21.00 h to 07.00 h and analysed in two separate sections: before midnight, when people are typically going indoors and outdoors their houses and after midnight, when people go indoors to sleep [64]. Indoor temperature and relative humidity were measured in each hut every 30 min using one data logger (TGU 4500, Tinytag, UK) located in the centre of the room and 1 m above the floor. Carbon dioxide was recorded every 30 sec with a data logger (1% CO2 + Rh/T Data Logger GasLab, Florida, USA) located between the beds near the head of the bed, 1.2 m above the floor according to the manufacturer's recommendation (Supplementary Fig. 1). Outdoor temperature, relative humidity, wind speed, wind direction and precipitation were recorded every 30 min using an automatic weather station (MiniMet, Skye Instruments, Llandrindod Wells, UK), located 10 m from the line of the huts, in the middle of the row of huts.

3.3.6 Statistical analysis

The analysis used IBM SPSS Statistics 27 and Stata version 17. The sample size was estimated using a computer simulation based on data from a study conducted in the same area in 2017 [83], in which the mean number of *An. gambiae* s.l. collected indoors over 25-nights was 6.4 mosquitoes (SD 7.1) and supported by a study conducted in 2019 in the same location and huts [147], where the mean number of *An. gambiae* s.l. collected indoors over 40 nights was 53 (SD 56). The present study was thus powered to detect an intervention that reduces the number of mosquitoes found indoors by at least 75 % at the 5 % level of significance and 90 % power. In the simulation, the 4 x 4 Latin square was repeated from three to 10 times (i.e. 12 to 40 nights). The simulation showed that eight, 4 x 4 Latin squares would provide sufficient power to detect a 75% reduction in mosquito hut entry (i.e. 32 nights of collections). Here, we only report the results of nights 5 to 36 (n=32 nights) since nights 1-4 collected few mosquitoes and nights 5 to 36 had the same men in each pair of sleepers. We used the initial period to prime the houses with human scent and make them more attractive to mosquitoes.

To assess the adjusted effect of different ground floor barriers to mosquito hut entry and indoor climate we used a generalised estimating equation (GEE) using a negative binomial model with a log link function for mosquito count data and a normal distribution with identity link for temperature and carbon dioxide, since they were continuous variables and normally distributed. In addition to hut height, we included hut treatment, hut position, sleeper pair and number of nights in the model as fixed effects. This allowed the adjusted analysis to show the effect of house typology without being impacted by other factors in the experimental huts. The computed mean ratio is the estimated ratio of mosquitoes associated with the intervention in relation to the control hut and is also presented as protective efficacy, the reduction in mosquitoes associated with the intervention. GEEs are usually used in the analysis of clinical trials and biomedical studies, to assess the effect of only one factor over a period of time and to allow for repeat measures in the same huts [133]. To examine the relationship between carbon dioxide concentration and covariates, we used linear regression. Polar plots were used to depict the direction and strength of the wind during the day and night. A linear regression model was used to examine the relationship between female *An. gambiae* and *Mansonia* spp.

3.3.7 Ethics statement

The study was approved by The Gambia Government and Medical Research Council's joint ethics committee (Reference number 19174; June 29, 2020) and the Department of Biosciences ethics committee, Durham University, UK (June 24, 2020).

3.4 Findings

3.4.1 Entomology

A total of 28,629 male and female mosquitoes were collected in the experimental huts using light traps and aspirators over 32 nights. Of these, 3,768 (13 %) were female *An. gambiae* s.l., 21,982 (77 %) female *Mansonia* spp, 2,441 (9 %) female *Culex* spp. and the rest were other male and female anophelines and *Aedes aegypti* (Appendix 1). PCR analysis identified female members of the *An. gambiae* complex as *An. coluzzii* (77.5 %, 93/120), *An. arabiensis* (20%, 20/120), and *An. gambiae* s.s. (2.5 %, 3/120). Mosquito numbers were low during the first week of the study by rose towards the end of August with large variations from week to week (Figure 3.4). Numbers of *Mansonia* spp. increased during the study and were consistently greater each night than the number of female *An. gambiae*.

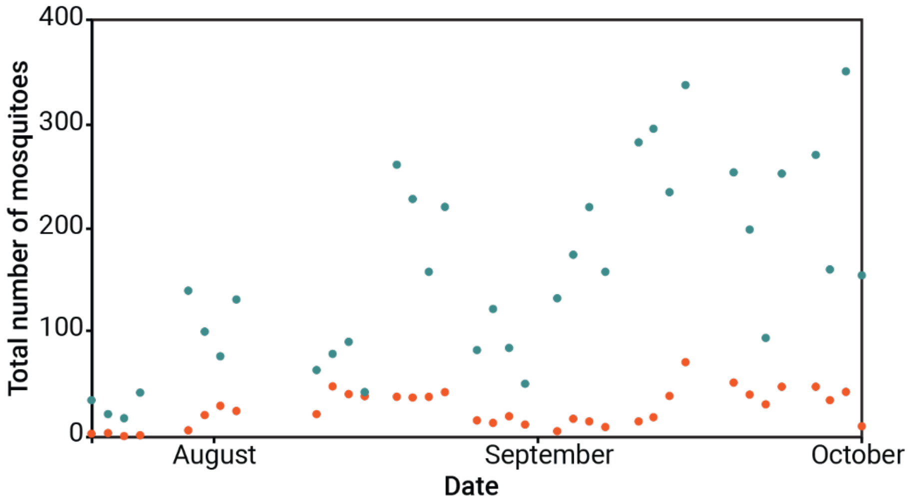

Figure 3. 4 Relative abundance of *An. gambiae* s.l. and *Mansonia* spp. collected each night during the study.
Orange dots = *An. gambiae* and green dots = *Mansonia* spp.

There was a linear relationship between the total numbers of female *An. gambiae* and *Mansonia* spp. captured in each hut each night (Figure 3.5; adjusted R^2 = 0.401, df= 142, p= < 0.001). This relationship was stronger in the house on the ground (Table 3.2; adjusted R^2= 0.559, df= 34, p= < 0.001) compared to the total numbers in all huts (Table 3.2). Elevated houses with open ground storey (Adjusted R^2= 0.326, df= 34, p= < 0.001), air-permeable walls on the ground storey (Adjusted R^2= 0.190, df= 34, p= 0.005) and solid walls on the ground (Adjusted R^2= 0.332, df= 34, p= < 0.001) showed a weaker relationship compared to the total numbers in all huts. Despite the different house treatments, the analysis shows both mosquito species are behaving similarly in the hut on the ground and this behaviour differs more once the height of the hut increases.

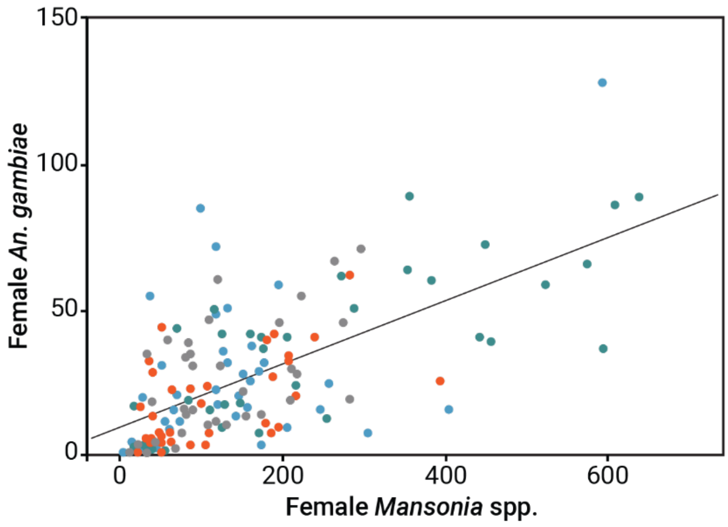

Figure 3. 5 Relationship between the number of *An. gambiae* s.l. and *Mansonia* spp. in nightly collections from each hut.
Turquoise dots = hut on the ground (control), orange dots = raised hut with free ground storey, light blue dots = raised hut with air-permeable walls underneath, grey dots = raised hut with solid walls underneath and black line = linear relationship between species.

Table 3. 2 Linear regression model.
Relationship between female *An. gambiae* and *Mansonia* spp.

	Adjusted R square	df	p value
All huts	0.401	34	< 0.001
Hut on the ground	0.559	34	< 0.001
Raised hut with open ground storey	0.326	34	< 0.001
Raised hut with air-permeable walls on the ground storey	0.190	34	0.005
Raised hut with solid walls on the ground storey	0.332	34	< 0.001

Unadjusted mean nightly indoor density of female *An. gambiae* s.l. was 39 (95% CI 30 to 48) in the hut on the ground, 20 (95% CI 15 to 26), in the raised hut with an open ground storey, 31 (95% CI 21 to 40) in the hut with air-permeable walls and 27 (95% CI 21 to 34) in the hut with solid walls (Figure 3.6).

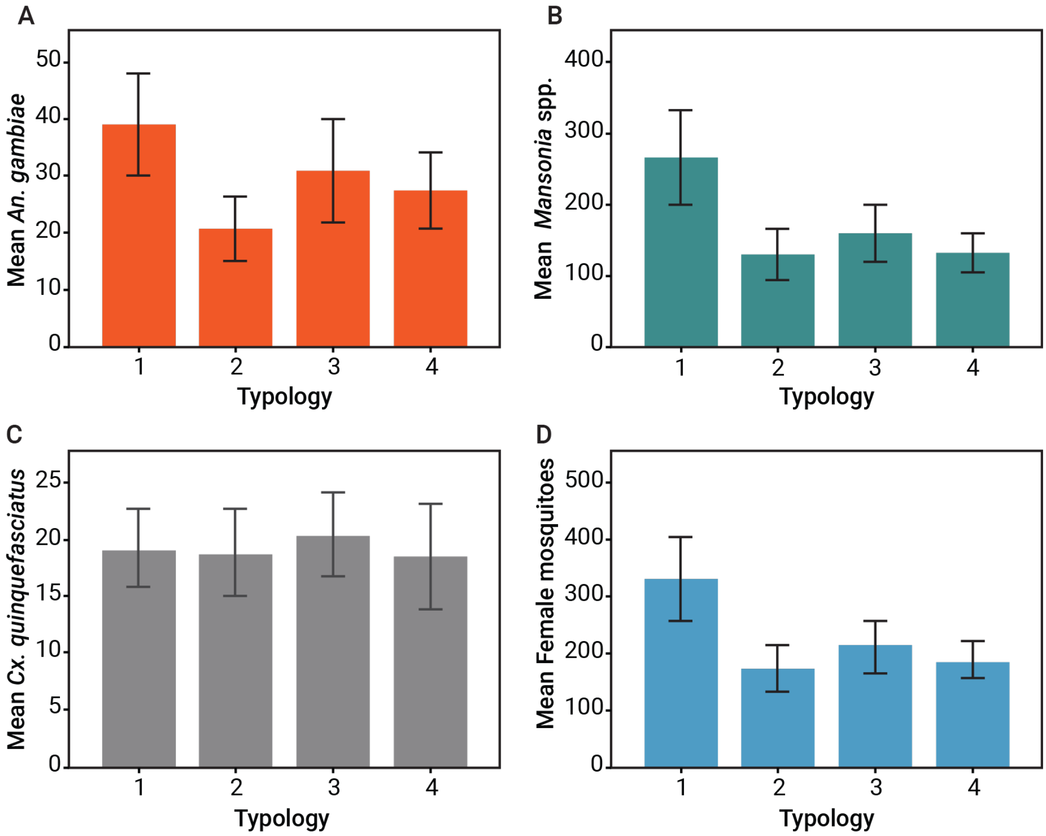

Figure 3. 6 Unadjusted mean numbers female mosquito hut entry in different hut at different heights and with different treatment on ground storey.
A= *An. gambiae*, B= *Mansonia* spp., C= *Culex quinquefasciatus*, D= all mosquitoes. 1 = hut on the ground (control), 2 = raised hut with open ground storey, 3 = raised hut with air-permeable walls underneath and 4 = raised hut with solid wall underneath. Error bars are 95 % confidence intervals. NB scales differ for each mosquito group.

The adjusted analysis, allowing for nights, sleeper pair and hut position, showed that the number of female *An. gambiae* entering the elevated huts was reduced in all elevated huts compared to the comparator on the ground. There were 53 % (95 % CI 47 to 58%) fewer female *An. gambiae* in the hut at 2 m with an open ground storey, 24 % fewer (95% CI 9 to 36 %) in the hut at 2 m with air-permeable walls on the ground storey and 31 % (95 % CI 24 to 37 %) fewer in the hut at 2 m with solid walls on the ground storey, compared to the hut at 0 m (Table 3.3). Similar results were seen with *Mansonia* spp. and total female mosquitoes, but not *Culex* spp. A second adjusted analysis only including the elevated huts at 2 m and using the hut with open ground storey as reference showed 63 % (95% CI 36 to 96 %) more female *An. gambiae* in the hut with air-permeable walls on the ground storey and 45 % (95% CI 36 to 56 %) more in the hut with solid walls. Increase of indoor mosquito density in this analysis was replicated for *Mansonia* spp. and total female mosquitoes, but not *Culex* spp.

3.4.2 Environmental measurements

Huts were consistently 3 ºC warmer than outside temperature (Figure 3.7). Indoor temperature declined steadily during the night from 29.5 ºC at 21.00 h to 25.4 ºC at 07.00 h.

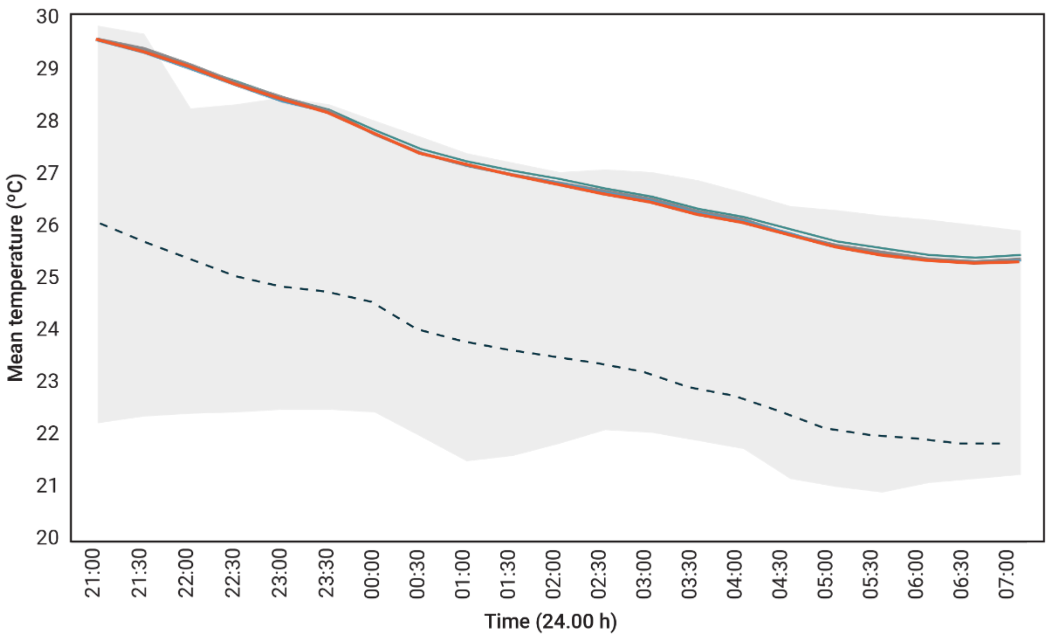

Figure 3. 7 Unadjusted mean temperature recorded In experimental huts at different heights and with different treatment on the ground storey and analysis.
Gray area = minimum and maximum outdoor temperature levels, Turquoise line = hut on the ground (control), orange line = raised hut with open ground storey, light blue line = raised hut with air-permeable walls on the ground storey, grey line = raised hut with solid wall on the ground storey and dashed line = outdoor values.

Multivariate analysis, adjusting for confounders showed a borderline significant reduction of 6% (95 % CI 0 to 13) in indoor temperature during the first part of the night in a raised hut with air-permeable walls in the ground storey compared with the hut at ground level (Table 3.4). During the second part of the night the raised hut with solid walls on ground storey had a 7 % (95 % CI 0 to 14) lower temperature compared with the control hut on the ground.

Table 3. 3 Mean female mosquitoes collected in experimental huts at different heights and with different treatment on ground storey and adjusted analysis.

Generalized linear modelling results, adjusted for hut position, sleeper pair and number of night. Figures in parentheses are 95 % confidence intervals.

Hut typology	Mean No.	Dif. from control hut (95% CIs)	Protective efficacy (95% CIs)	p value	Mean No.	Dif. from control hut (95% CIs)	Protective efficacy (95% CIs)	p value
Female *An. gambiae*								
Hut on the ground	1259	Reference	..	..	..	..	..	..
Raised hut with open ground storey	655	0.47 (0.42 to 0.53)	- 53 % (-47 to -58)	< 0.001	655	Reference	..	..
Raised hut with air-permeable ground storey	981	0.76 (0.64 to 0.91)	- 24 % (-9 to -36)	0.002	981	1.63 (1.36 to 1.96)	63 % (36 to 96)	< 0.001
Raised hut with solid walls on ground storey	873	0.69 (0.63 to 0.76)	- 31 % (-24 to -37)	< 0.001	873	1.45 (1.36 to 1.56)	45 % (36 to 56)	< 0.001
Female *Mansonia* spp.								
Hut on the ground	240	Reference	..	..	..	..	..	..
Raised hut with open ground storey	120	0.48 (0.41 to 0.57)	- 52 % (-43 to -59)	< 0.001	120	Reference	..	..
Raised hut with air-permeable ground storey	142	0.62 (0.54 to 0.72)	- 38 % (-28 to -46)	< 0.001	142	1.31 (1.27 to 1.36)	31 % (27 to 36)	< 0.001
Raised hut with solid walls on ground storey	121	0.54 (0.49 to 0.59)	- 46 % (-41 to -51)	< 0.001	121	1.14 (1.07 to 1.21)	14 % (7 to 21)	< 0.001
Female *Culex* spp.								
Hut on the ground	8535	Reference	..	..	..	..	..	..
Raised hut with open ground storey	4145	0.92 (0.83 to 1.03)	- 8 % (-17 to 3)	0.150	4145	Reference	..	..
Raised hut with air-permeable ground storey	5021	1.06 (0.87 to 1.30)	6 % (-13 to 30)	0.550	5021	1.13 (0.95 to 1.36)	13 % (-5 to 36)	1.356
Raised hut with solid walls on ground storey	4281	0.89 (0.85 to 0.93)	- 11 % (-7 to -15)	< 0.001	4281	0.34 (0.93 to 0.80)	- 66 % (-20 to -7)	1.080
All mosquitoes								
Hut on the ground	10478	Reference	..	..	..	..	..	..
Raised hut with open ground storey	5451	0.52 (0.45 to 0.59)	- 48 % (-41 to -55)	< 0.001	5451	Reference	..	..
Raised hut with air-permeable ground storey	6715	0.69 (0.60 to 0.79)	- 31 % (-21 to -40)	< 0.001	6715	1.34 (1.33 to 1.35)	34 % (33 to 35)	< 0.001
Raised hut with solid walls on ground storey	5814	0.59 (0.55 to 0.64)	- 41 % (-36 to -45)	< 0.001	5814	1.15 (1.10 to 1.19)	15 % (10 to 19)	< 0.001

Table 3. 4 Environmental outdoors and indoors measurements and adjusted analysis.

General linearised modelling results, adjusted for hut position, sleeper pair and night. Figures in parentheses are 95 % confidence intervals.

	Average temperature from 21.00 h to 23.30 h			Average temperature from 00.00 h to 07.00 h			Average temperature from 21.00 h to 23.30 h			Average temperature from 00.00 h to 07.00 h		
	Average (ºC)	**Difference from control hut**	**p value**	**Average (ºC)**	**Difference from control hut**	**p value**	**Average (ºC)**	**Difference from control hut**	**p value**	**Average (ºC)**	**Difference from control hut**	**p value**
Outdoors	26.2 (25.6 to 26.9)	..	..	24.6 (25.6 to 26.9)	..	..	..	..	..	..	..	..
Hut on the ground	28.9 (28.1 to 29.7)	Reference	..	26.6 (26.1 to 27.1)	Reference	..	..	..	..	..	..	..
Raised hut with open ground storey	28.9 (28.1 to 29.7)	0.98 (0.83 to 1.16)	0.832	26.5 (25.9 to 27.0)	0.90 (0.75 to 1.07)	0.222	28.9 (28.1 to 29.7)	Reference	..	26.5 (25.9 to 27.0)	Reference	..
Raised hut with air-permeable ground storey	28.8 (28.1 to 29.6)	0.94 (0.87 to 1.00)	0.061	26.5 (26.0 to 27.0)	0.91 (0.81 to 1.03)	0.138	28.8 (28.1 to 29.6)	0.96 (0.85 to 1.09)	0.513	26.5 (26.0 to 27.0)	1.02 (0.93 to 1.18)	0.724
Raised hut with solid walls on ground storey	28.9 (28.1 to 29.7)	1.00 (0.95 to 1.06)	0.896	26.5 (26.0 to 27.1)	0.93 (0.86 to 1.00)	0.040	28.9 (28.1 to 29.7)	1.02 (0.94 to 1.11)	0.613	26.5 (26.0 to 27.1)	1.03 (0.94 to 1.14)	0.501
	Average relative humidity from 21.00 h to 23.30 h			**Average relative humidity from 00.00 h to 07.00 h**			**Average relative humidity from 21.00 h to 23.30 h**			**Average relative humidity from 00.00 h to 07.00 h**		
	Average (%)	**Difference from control hut**	**p value**	**Average (%)**	**Difference from control hut**	**p value**	**Average (%)**	**Difference from control hut**	**p value**	**Average (%)**	**Difference from control hut**	**p value**
Outdoors	84.9 (83.2 to 86.7)	..	..	89.4 (88.3 to 90.4)	..	..	..	..	..	..	..	..
Hut on the ground	75.2 (73.5 to 76.8)	Reference	..	80.7 (79.8 to 81.7)	Reference	..	..	..	..	..	..	..
Raised hut with open ground storey	75.1 (73.2 to 76.9)	0.91 (0.38 to 2.19)	0.832	81.0 (80.0 to 82.1)	1.36 (0.70 to 2.64)	0.362	75.1 (73.2 to 76.9)	Reference	..	81.0 (80.0 to 82.1)	Reference	..
Raised hut with air-permeable ground storey	75.2 (73.5 to 77.0)	1.08 (0.55 to 2.14)	0.823	80.9 (79.9 to 81.9)	1.20 (1.11 to 1.30)	< 0.001	75.2 (73.5 to 77.0)	1.19 (0.61 to 2.32)	0.612	80.9 (79.9 to 81.9)	0.88 (0.49 to 1.33)	0.552
Raised hut with solid walls on ground storey	75.1 (73.4 to 76.8)	0.94 (0.48 to 1.86)	0.866	81.0 (79.9 to 82.0)	1.25 (0.95 to 1.65)	0.117	75.1 (73.4 to 76.8)	1.04 (0.62 to 1.75)	0.890	81.0 (79.9 to 82.0)	0.92 (0.68 to 1.25)	0.582
	Average carbon dioxide from 21.00 h to 23.30 h			**Average carbon dioxide from 00.00 h to 07.00 h**			**Average carbon dioxide from 21.00 h to 23.30 h**			**Average carbon dioxide from 00.00 h to 07.00 h**		
	Average (ppm)	**Difference from control hut**	**p value**	**Average (ppm)**	**Difference from control hut**	**p value**	**Average (ppm)**	**Difference from control hut**	**p value**	**Average (ppm)**	**Difference from control hut**	**p value**
Outdoors	598 (548 to 648)	..	..	570 (537 to 602)	..	..	..	..	..	..	..	..
Hut on the ground	836 (782 to 891)	Reference	..	766 (725 to 806)	Reference	..	..	..	..	..	..	..
Raised hut with open ground storey	788 (736 to 840)	0.65 (0.40 to 1.08)	0.095	738 (704 to 771)	0.81 (0.73 to 0.89)	< 0.001	788 (736 to 840)	Reference	..	738 (704 to 771)	Reference	..
Raised hut with air-permeable ground storey	798 (753 to 843)	0.53 (0.43 to 0.66)	< 0.001	727 (693 to 761)	0.58 (0.44 to 0.77)	< 0.001	798 (753 to 843)	0.83 (0.55 to 1.27)	0.396	727 (693 to 761)	0.72 (0.60 to 0.87)	0.001
Raised hut with solid walls on ground storey	801 (758 to 844)	0.70 (0.45 to 1.11)	0.127	725 (694 to 755)	0.71 (0.58 to 0.89)	0.002	801 (758 to 844)	1.10 (0.75 to 1.62)	0.621	725 (694 to 755)	0.88 (0.72 to 1.08)	0.225

Wind was predominantly from the north-west and mean wind speed was 0.50 ms^{-1} (95% CIs 0.45 to 0.63) from 20.00-23.59 h and 0.58 ms^{-1} (95% CIs 0.56 to 0.67) from 00.00-06.59 h (Figure 3.8).

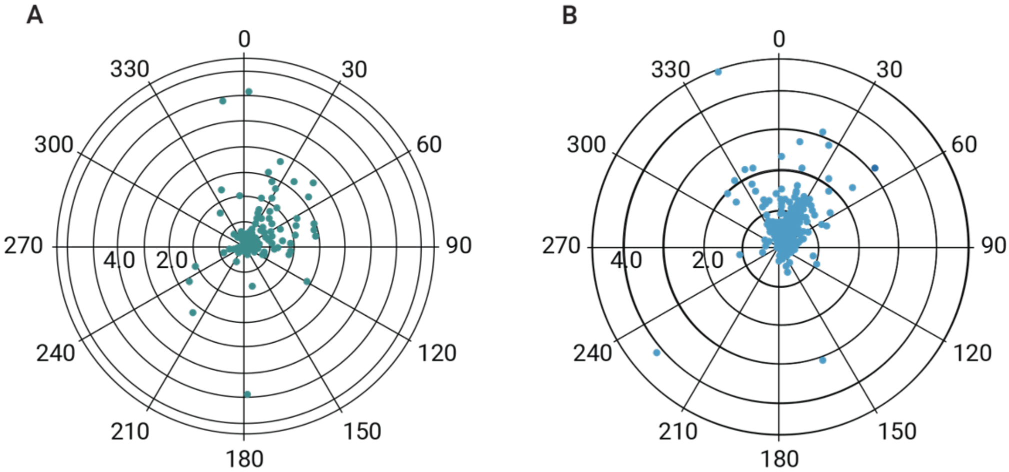

Figure 3. 8 Wind direction and speed during experimental nights.
Where A = first part of the night (21.00 h to 23.30 h) and B = second part of the night (00.00 h to 07.00 h).

Overall unadjusted levels of carbon dioxide indoors were 32 % higher than outdoors. Carbon dioxide levels indoors were high after the men entered the huts before gradually declining during the night with an uptick in concentration from 05.30 h to 07.00 h (Figure 3.9). Huts on the ground had higher levels of carbon dioxide than those elevated to 2 m above the ground (Table 3.4).

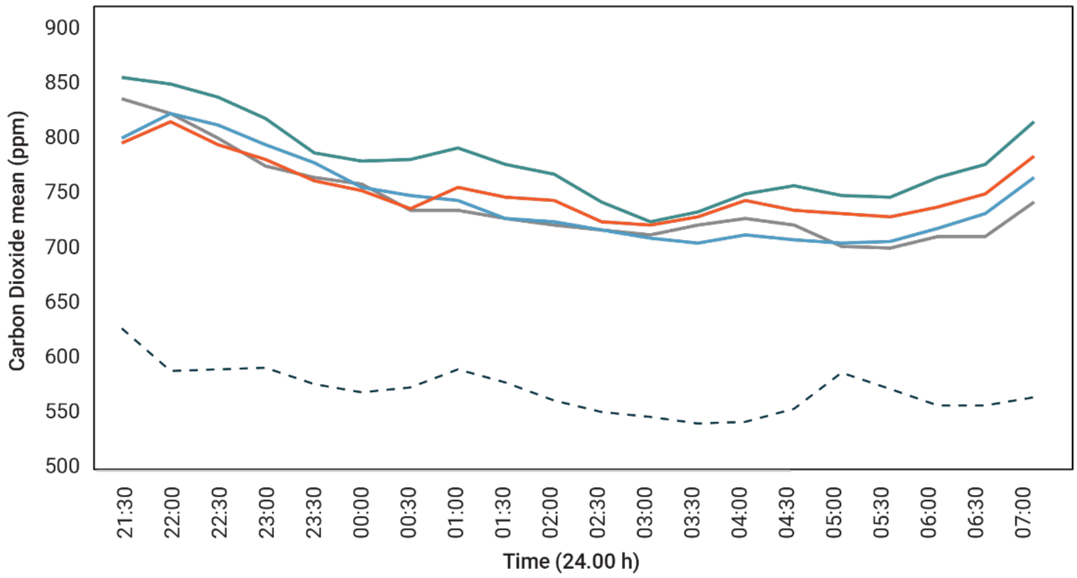

Figure 3. 9 Unadjusted mean carbon dioxide from 21.00 h to 07.00 h in different house typologies.
Where purple line = hut on the ground (control), green line = raised hut with open ground storey, light blue line = raised hut with air-permeable walls on the ground storey, orange line = raised hut with solid walls on the ground storey and dashed line = outdoor values.

In the adjusted analysis, before midnight there was a 47 % (95 % CI 34 to 57) decline in carbon dioxide at 2 m with air-permeable walls on the ground storey compared with the control house (Table 3.4). After midnight, there was a decrease of 19 % (95 % CI 11 to 27) in the raised hut with an open ground storey and a 32 % reduction (95 % CI 23 to 56) in the raised house with air-permeable walls on the ground storey compared with the control house.

3.5 Discussion

The findings of this chapter establish how the permeability of the ground storey immediately below a hut elevated 2 m above the ground affects indoor mosquito entry, indoor temperature and carbon dioxide levels. As found previously, the number of female *An. gambiae* mosquitoes collected in all elevated huts were lower than the reference hut situated on the ground [147]. Elevated huts with no walls on the ground storey had 53 % fewer mosquitoes than the comparator hut situated on the ground. This level of protection was slightly less than the 68 % reported in the previous chapter, and this decrease in efficacy may be a result of adding a large wooden staircase to one side of each elevated hut in the present study. Mosquito hut entry was, affected by the permeability and presence of walls immediately below the elevated huts. Huts with screened walls under the hut resulted in 31 % fewer house-entering mosquitoes and solid walls 24 % less than the hut at ground level. An analysis of mosquito counts restricted to elevated huts showed that huts with screened walls underneath had 63 % more female *An. gambiae* s.l. and those with solid walls 45 % more than the raised hut without walls underneath. Similar levels of protection were observed with *Mansonia* spp. and when all mosquitoes were considered. This was not the case for *Culex* spp., however, where there was no reduction in house entry in elevated huts compared to those on the ground. A similar finding was found in the previous chapter, so this is likely to be a true result reflecting the habits of these mosquitoes. Unlike *An. gambiae* s.l. and *Mansonia* spp. which fly low to the ground when blood-questing and are probably influenced by higher wind speed at higher altitude, *Culex* spp. are collected at higher altitudes [77,148], which is probably related to their habit of feeding on birds at night [149]. The linear regression analysis confirms the protective effect of elevating a house, as female *An. gambiae* behaved similar to *Mansonia* spp. mosquitoes at ground level but not so much at higher altitudes.

The major finding is that screened or solid walls on the ground floor will reduce the entry of *An. gambiae* s.l. into an inhabited room on the second storey, but less effectively than a hut that is open on the ground floor. These findings are supported by a series of studies carried out in The Gambia in the 1970s by Gillies and Wilkes conducted in the same area [107]. The second experiment was conducted with a 6m high circular fence made of mosquito screening and a human bait in the centre and found that mosquitoes flew up and over the fence towards the bait. Presumably, in our experiments mosquitoes are also rising up the screened and solid walls, following carbon dioxide plumes emanating from the gaps above and below the doors in the elevated hut. In contrast, wind contributed to disperse carbon dioxide more effectively in the hut that was open underneath. In a study in Tanzania [127], elevated houses with a screened second-storey and a screened or solid ground floor had 96 % (95% CI 92-98) fewer mosquitoes in the bedrooms first storey compared with houses at ground level. This finding supports our findings and suggest that elevating a house is an effective measure for preventing mosquito house entry.

As well as mosquitoes orientating to odour, visual orientation is also likely to be important. Gillies and Wilkes conducted a series of experiments to determine the importance of visual features in the host-seeking behaviour of mosquitoes [150]. In these experiments they demonstrated that mosquitoes were attracted to shapes. In this case the air-permeable and solid ground floor enclosures could have represented a large dark shape that then guided mosquitoes towards each hut. Snow speculated that 'at higher levels [above 2m], where visual contact with the ground may be lost, direct orientation to the obstacles [in this case the elevated hut] could be increasingly important' [151]. Our results suggest that raising a hut several metres above the ground reduces the entry of malaria mosquitoes, but that this protection is reduced if the space under the hut is walled with either semi-permeable or solid walls. A recent study conducted in Tanzania showed that light from the CDC light trap increased the collections as mosquitoes where attracted to the light source [117]. In our case the attraction to the light source located at the mosquitoes usually flying altitude (hut on the ground) might have increased the collections in the control hut.

In this study indoor temperature was several degrees warmer than outdoor temperatures, but both decreased gradually during the night. There was no discernible reduction in indoor temperature with increasing height or in elevated huts whether the ground storey was walled or not. This may be misleading since our huts on the ground were supported by four concrete plinths, one at each corner, with a space directly under most of the hut floor acting as insulation preventing the hut being warmed from the ground. Thus, our huts on the ground were probably cooler than those constructed directly on the ground and for practical purposes all of our huts had a space between the ground and the hut's floor.

Indoor carbon dioxide levels were 200 ppm higher in the huts compared with outdoor levels, providing a powerful source of attraction for malaria mosquitoes. The highest indoor carbon dioxide concentrations were at the beginning of the night, 21.00 h but then declined slowly to the lowest level at 03.00 h. A peak in indoor concentration levels took place at 05.30 h from where levels continued increasing until the sleepers left the huts at 07:00 h. The final morning increase might be due the natural circadian rhythm, with the body preparing to become active nearer dawn [137,138] and an increase in physical activity immediately before leaving the huts. Indoor carbon dioxide concentrations where higher in the hut located on the ground through the night, this might be due to the presence of higher winds as the huts are raised from the ground. Differences in indoor carbon dioxide concentrations in the raised huts might be due to the effect of the wind flowing up next to the solid walls preventing carbon dioxide exiting from the hut. In contrast to what happened to temperature levels, elevated huts were impacted by the space between the hut's floor and the ground reducing their indoor carbon dioxide levels.

In recent decades, sub-Saharan Africa has experienced rapid urbanization, with migration from rural areas to the cities and the rising birth rate leading to 1.23 billion people living in African cities by 2050 [152]. The urgent need for new houses led to the uncontrolled growth of poorly-built constructions, commonly located in informal settlements in urban areas. Recently, materials produced during the modern period like concrete blocks or corrugated metal roofing sheets are leading the house improvement phenomenon and market in sub-Saharan Africa [61]. They have played an important role in the increase of the percentage of houses built with finished materials from 32 % (29-33 %) in 2000 to 51 % (49-54 %) in 2015 [85]. As a consequence of globalization these materials are imported into sub-Saharan countries from China and India and have overtaken local construction markets and influenced design through massive constructions that serve as contemporary examples in the region [153]. With population growth and migration to cities, land becomes scarce, in that context vertical construction is a solution to allocate more people in a plot of land. In peri-urban areas, like the ones created with rural-urban migration and urban expansion, where environmental conditions are more similar to rural than to urban contexts, vertical housing is a protective measure from malaria mosquitoes, but may not protect against nuisance biting by *Culex* mosquitoes [154,155]. The increase of vertical houses will also have implications in the pressure on basic services offered by the state, where electrical and water consumption will be more focalized and there will be a need of better infrastructure.

There are several limitations to this study. Firstly, the walls we used for the experimental huts were chosen because of their lightweight and do not represent the actual materials used in local villages. This makes the huts' thermal properties different from real-life. Secondly, the men entered the huts at 21:00 h and stayed until 07:00 h the next morning. This differs from normal behaviour where many would stay outside until midnight [64] and leave their houses for Fajr, morning prayer before sunrise. Thirdly, the huts host only two male adults because of the experimental design, in the context where the study was conducted around four people, between adults and children, will normally be sleeping in a single-roomed house (M.Pinder, unpublished data) with adult men often sleeping on their own.

The findings of this chapter show that the number of malaria mosquitoes entering a hut is markedly reduced when the hut is raised 2 m above the ground and that if the space below the hut is walled in with either screening or solid walls, the protective effect is reduced. It is recommend leaving the ground floor free when building multiple storey buildings. This will protect inhabitants from mosquito bites and reduce indoor temperature, making houses more comfortable and people willing to use an insecticide-treated net. This research is likely to be especially relevant to peri-urban areas of sub-Saharan Africa where new constructions are most likely to take place.

Chapter 4. Effect of roof colour on indoor temperature and human comfort levels, with implications for malaria control: a pilot study using experimental houses in rural Gambia

4.1 Abstract

4.1.1 Background

In rural sub-Saharan Africa, thatch roofs are being replaced by metal roofs. Metal roofing, however, increases indoor temperatures above human comfort levels and risk residents not using their insecticide-treated nets, the principal malaria control tool in the region. We assessed whether the colour of a metal roof would affect indoor temperature and human comfort.

4.1.2 Methods

Two identical, experimental houses were constructed with metal roofs in rural Gambia. Roof types were: original bare-metal, painted with red oxide primer or white gloss, to reflect solar radiation. Pairwise comparisons were run in six, five-night blocks during the malaria season 2018. Indoor climate was measured in each house and multivariate analysis used to compare indoor temperatures during the day and night.

4.1.3 Findings

From 21.00 h to 23.59 h, when most residents decide whether to use an insecticide treated net or not, the indoor temperature of a house with a bare metal roof was 31.5 ºC (95%CI = 31.2 to 31.8 ºC), a red roof, 30.3 ºC (95%CI= 30.0 to 30.6) and a white roof, 29.8 ºC (95%CI= 29.4 to 30.1). During the same period, red-roofed houses were 1.23 ^{o}C cooler (95%CI=1.22 to 1.23) and white roofs 1.74 ^{o}C cooler (95%CI=1.70-1.79) than bare-metal roofed houses ($p<0.001$). Similar results were found from 00.00 h to 06.00 h. Maximum daily temperatures were 0.93 ^{o}C lower in a white-roofed house (95%CI= 0.10 to 0.30, $p<0.001$), but not a red roof (mean maximum temperature difference=0.44 ^{o}C warmer, 95% CI= 0.43-0.45, $p=0.081$), compared with the bare-metal roofed houses. Human comfort analysis showed that from 21.00 h to 23.59 h houses with white roofs (comfortable for 87% time) were more comfortable than bare-metal roofed houses (comfortable for 13% time; odds ratio = 43.7, 95% CIs 27.5-69.5, $p <0.001$). The cost of painting a metal roof white is approximately 31 to 68 USD.

4.1.4 Interpretation

Houses with a white roof were consistently cooler and more comfortable than those with a bare metal roof. Painting the roofs of houses white is a cheap way of making

a dwelling more comfortable for the occupants and could potentially increase bed-net use in hot humid countries.

4.1.5 Funding

Global Challenges Research Fund and Sir Halley Stewart Trust, United Kingdom

4.2 Introduction

Between 2000 and 2015, the percentage of improved houses, classified as those with improved water and sanitation, sufficient living area and constructed from durable materials, increased from 8.2 % to 18.4 % in rural sub-Saharan Africa and from 32.3 % to 53.2 % in urban areas [85]. At the same time, the region is experiencing an unprecedented increase in population and it is estimated that by 2050, there will be an extra one billion people living in the region [124], mainly in informal settlements [156]. This rise in population will be accompanied by a huge demand for new and improved housing.

Many of these new homes will be built in malaria-endemic areas and will require novel methods of disease control. Currently, one of the principal tools for malaria control are insecticide-treated nets (ITNs) [2], which provide protection against malaria vectors feeding indoors at night. Correct use of ITNs can be a highly effective intervention [2]. In many countries, however, especially when it is hot and humid, nets are considered too hot to sleep under [3]. Simple solutions for cooling down houses at night are thus required to increase net usage and reduce malaria prevalence.

One of the most obvious and rapid transformations in housing seen in sub-Saharan Africa is that metal roofs are replacing traditional thatched roofs [85]. Studies in the hot, humid tropics have shown that metal-roofed houses are hotter during the day than those that have thatched roofs and they remain appreciably hotter well into the night [83,102,103]. Thus whilst, high indoor temperatures experienced in metal-roofed houses during the day increases the mortality of malaria mosquitoes resting indoors [58], thereby reducing transmission, they also increase the risk that people at night will not sleep under a net [3] due the remaining heat emitted mainly by walls.

Typically, houses in sub-Saharan Africa have a roof built from a single layer of thin steel corrugate sheeting, coated with zinc for increased durability and protection against corrosion. Roofs protect the main structure of the house and in harsh environments like much of the region are exposed to high levels of solar radiation, temperature, rain and wind. Thus, over time, metal corrodes due to oxidation caused by contact with water [157], salt, dust and soot [101,158], causing the roof to rust. This process of oxidation changes the colour of the roof from silvery grey to dark red (Figure 4.1) and the surface becomes rugous, both factors that affect the physical characteristics of the roof. To slow oxidation, further prolong the useful life of zinc treated sheeting, and enhance the appearance of these houses, pre-painted corrugate sheets of different colours can be purchased at a higher cost price, alternatively the zinc-coated roofing is frequently painted, after purchase by householders.

Roofs transmit the heat they absorb from solar radiation to the indoor space they cover, therefore in hot environments, their characteristics are crucial to keep the house cool. Having a light-coloured or white roof can reduce indoor temperatures. In Arizona, USA, surface temperatures of white roofs were 20 ºC to 30 ºC less than those of grey or brown roofs as a result of the greater reflectance of white roofs [159]. High solar reflectance will reduce the heat transmitted to the indoor space. In India, painting metal roofs with solar reflective paint reduced indoor air temperatures by ~ 5 ºC at the hottest time of the day, compared to untreated houses [160].

Figure 4. 1 A new (left) and rusted metal roof (right) in a Gambian village.
(Lindsay, S., personal collection).

Here we examine the impact of colour of metal roofs on the indoor temperatures of basic housing in a tropical setting. In general, dark colours absorb more heat from the sun than lighter colours. Thus, in this study it was hypothesised that a red roof would result in higher room temperatures compared with a white roof and an unpainted non-corroded zinc coated steel roof. This hypothesis was tested using experimental houses in rural Gambia.

4.3 Methods

4.3.1 Study design

This was an experimental study using two identical uninhabited houses with metal saddle-shaped roofs constructed from corrugated, galvanised metal sheeting carried out in the field. Three types of roof were tested: (A) bare metal, (B) a roof painted with red oxide primer and (C) one painted with white gloss paint. After the baseline week, when both houses had unpainted metal roofs, in weeks 2, 3 and 4, one roof was painted each week with either red or white paint and in week 5 the colours were switched (Figure 4.2). Indoor and outdoor temperature and relative humidity were monitored continuously during the study. The primary objective was to determine whether indoor temperature and thus, human comfort, changed according to the colour of the metal roof. The houses had two bamboo beds with mattresses but no inhabitants.

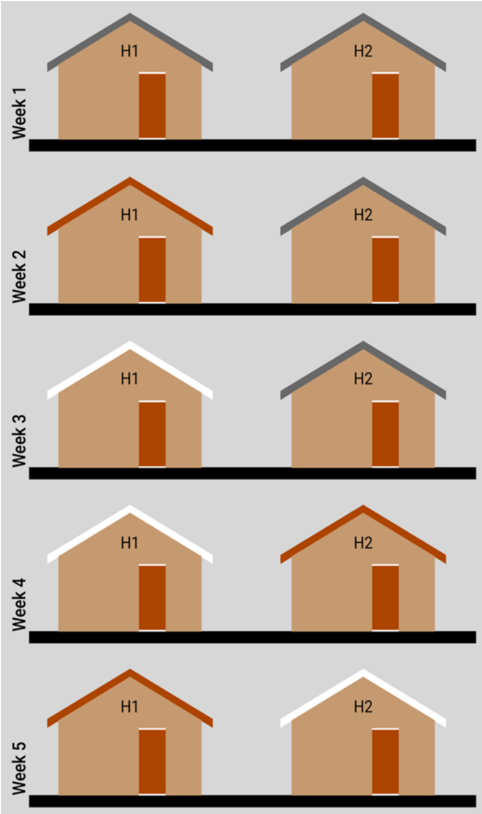

Figure 4. 2 Experimental schedule.
Where grey roof = bare metal roofs, red roof = red painted roofs and white roof = white painted roofs. H1 and H2 are house numbers.

Five, one weekly experiments were conducted, each one of five nights duration. In the baseline week, both houses had the same bare metal roofs to simulate typical metal-roofed houses found in local villages and to determine whether there were inherent differences in temperature between the two houses. Thereafter, each week one or both roofs was painted a different colour, first either red or white, using the schedule shown in Figure 4.2. Bare-metal roofs were first painted with red matt paint (Red Oxide paint, National Paints Factories, Dubai), used as a primer for metal surfaces, and then painted with white gloss (White Oil paint, National Paints Factories, Dubai). The roof colour was changed weekly in a progressive fashion to avoid having to return to bare-metal roofs. It also required a roof to be painted first with primer and then gloss paint to reduce the number of paint coats on the roof that could affect the heating and cooling of the roof. The first house to have a metal roof painted was randomly selected by flipping a coin.

4.3.2 Study area

The study took place at the Medical Research Councils Unit The Gambia's, field station at Wali Kunda (N 13° 34·25', W 14° 55·28'), located on the south bank of the River Gambia in the Central River Region, The Gambia. The study took place during the rainy season, from September 11st to October 21th 2017, when numbers of the malaria vector, *An. gambiae* s.l., are greatest [83].

4.3.3 Experimental houses

Construction of the experimental houses have been described in detail elsewhere [123]. Two experimental houses were the same size as the average one-roomed rural house, 10 m apart (Figure 4.3). Each house was constructed from mud blocks, covered with a thin mud and cement render and had a galvanised corrugated roof with closed eaves (the gap between the top of the wall and the roof), as is typical of metal-roofed housing in The Gambia. The dimensions of the roof were 4.80 m by 2.42 m and the corrugate metal was 0.14 mm thick. Each house was 4.20 m by 4.20 m in floor area and the walls were 2.20 m high. Both houses had three doors located on three different walls, and each door was 1.80 m high and 0.80 m wide. There were no windows in the houses, as is common in many rural homes in the region.

Figure 4. 3 Position of experimental houses and outdoor weather station.

4.3.4 Outcomes

Indoor temperature and relative humidity were measured in each house every 30 min using data loggers (TGU 4500, Tinytag, UK) positioned in the centre of the room, 1 m above the floor. Outdoor temperature and relative humidity were recorded every 30 minutes with a data logger inside a Stevenson screen located mid-way between the two houses. Thermal images of experimental houses were captured using a thermal imaging camera (FLIR ONE, FLIR Systems, USA).

4.3.6 Cost estimation

We estimated the cost of installing and, where appropriate, painting a gable roof for an average single-room rural Gambian house. The cheapest roofing option available in the market is corrugated galvanized steel which comes in a variety of sizes and thicknesses, with 1.85 m by 0.65 m being the most common. The experimental houses had 28 smaller metal sheets, each 0.65 m by 1.85 m, to cover the 23.23 m^2 roof area. To paint a red roof requires one coat of red oxide paint primer, whilst a white roof requires one coat of red oxide primer and two coats of white gloss over the primer. We estimated that for each coat of paint to cover an area of 23.23 m^2 requires 2.90 L of paint, assuming a coverage of 8 m^2 L^{-1}. (Coverage was taken from manufacturer technical specifications at www.hammerite.com, accessed on February 8th, 2021, Hammerite, Northumberland, UK). Thus, to paint a roof white, a householder would need 5 L of red oxide primer for the first coat and 10 L of white gloss paint for two additional coats. Paint costs would be further reduced by painting more than one house at a time, preventing waste of paint. An alternative would be to use pre-painted coloured metal sheets which have a high albedo [161]. Costs of labour, painting equipment and shipment were considered the same for each roof type so were not included in the analysis. We estimated the costs of materials from The Gambia and South Africa to explore ranges in prices. Costs are presented in USD based on an exchange rate of 1 Gambian dalasi = 0.019 USD and 1 South African Rand = 0.061 USD (Morningstar at Google accessed 19th October 2020).

4.3.7 Statistical analysis

The two primary outcomes were mean indoor temperature and human comfort in the first part of the night, when people choose whether to use a bed-net or not. Differences between outside and indoor temperatures were used to make comparisons between houses with different coloured roofs. Multivariate analysis linear regression was used to assess the effect of roof colour on indoor temperature, for indoor temperature and relative humidity, since both variables were continuous and normally distributed. In addition to roof colour, we included house position, coats of paint and collection night number in the model as fixed effects. Temperature was analysed in three periods: (1) 21.00 h to 23.59 h, going to bed, (2) 00.00 h to 6.59 h, sleeping, and (3) 07.00 h to 20.59 h, awake.

For the analysis of indoor temperature between houses we used IBM SPSS Statistics version 20 and Stata version 16. We considered this experiment to be a pilot exercise, designed to inform future studies about sample sizes. We used the LadyBug (LadyBug Products, Athol, ID, USA) software package to estimate the proportion of time putative occupants would spend in the so-called 'comfort zone' which is determined by indoor levels of temperature, relative humidity, indoor wind strength and the activity and clothing of the inhabitants. Readings that fall in the comfort polygon provide an estimated proportion of time that people would be comfortable, not too hot nor too cold. We assumed that from 21.00 h to 23.59 h two adults in each houses would be sitting chatting and wearing thin straight trousers and briefs, and from 00.00 h to 06.59 h the people inside the houses would be sleeping without sheeting. For each house typology, we calculated the proportion of time the indoor climate was within the comfort zone for both periods: when people retire to bed and when they are sleeping. Comparisons of human comfort were made using chi-square tests using Epi Info (version 7).

4.4 Findings

4.4.1 Environmental measurements

Both houses showed a similar pattern of daily temperature cycles (Figure 4.4). At night it was hotter indoors than outdoors, whilst during the late afternoon the temperatures were similar or hotter outdoors. Indoor temperatures warmed during the day, reaching maximum temperatures between 14.00 h to 18.00 h, before declining slowly during the night. In week one when both houses had bare metal roofs, house 1 had a maximum temperature of 35.6 ºC at 16.00 h and a minimum temperature 26.5 ºC at 06.00 h. In contrast, house 2, had a maximum temperature of 34.5 ºC at 14:30 h and the minimum at 06.00 h with 25.8 ºC. The maximum temperature in house 1 was more pronounced than house 2, which appeared flattened, probably due to the shade of tall trees that fell across the roof of house 2 in the late afternoon. Outdoor temperatures and relative humidity experienced during the study is shown in the supplementary material (Appendix 2).

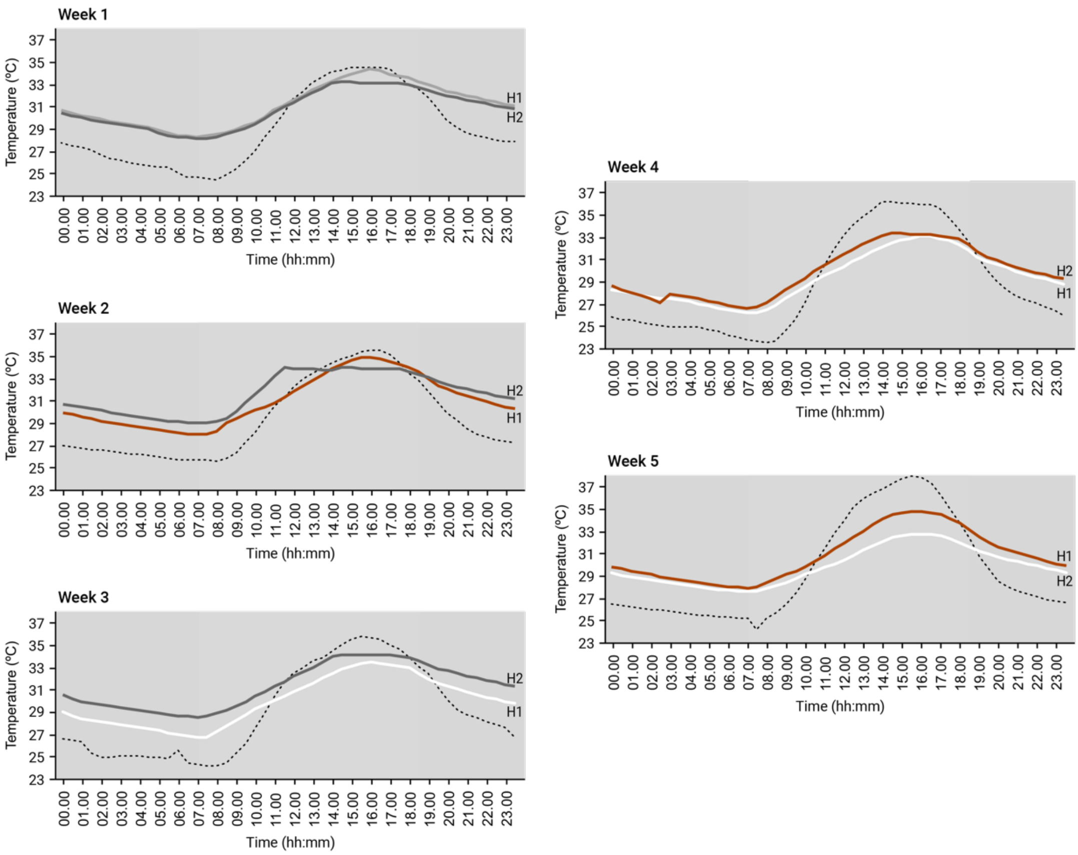

Figure 4. 4 Mean hourly temperature for each roof typology.
Where black line = bare metal roofs, red line = red painted roof, white line = white painted roofs and black dotted line = outdoor temperature. Light grey bars mark sunrise and sunset.

During the study, white roofs were consistently cooler throughout the day compared with the other roof types (Table 4.1, Figure 4.5). Red roofs were generally cooler than the metal roofs, except during the hottest part of the day between 15.00 h and 16.00 h.

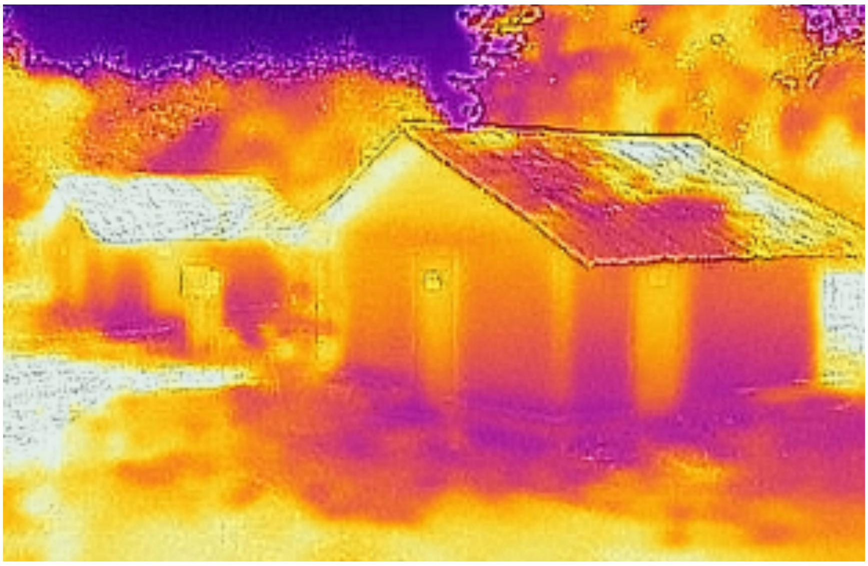

Figure 4. 5 Thermal image of the experimental houses taken in the afternoon. Lighter colours are hotter than darker colours. The house on the left has a red painted roof and the house on the right a white painted roof.

Both during the day and night, multivariate analysis adjusting for house position, number of paint coats and night number, showed that a house with a white roof was cooler than one with a bare-metal roof (Table 4.1). Red roof houses were also cooler than those with bare metal roofs during the night, but not during the day, and were not as cool as white roofed houses. There was no association between indoor temperatures and number of coats of paint on the roofs.

Table 4. 1 Indoor and outdoor temperatures at night and during the day.
Adjusted analysis for night, house position and number of coats of paint. Figures in parentheses are 95 % confidence intervals.

		Mean indoors temperature (°C)	Temperature difference indoors vs. outdoors (°C)	Temperature difference from control house (°C)	p value
Temperature from 00.00 h to 07.00 h	Metal	31.5 (31.5 to 31.8)	3.4 (2.1 to 3.6)	..	..
	Red.	30.3 (30.0 to 30.6)	3.1 (2.8 to 3.4)	1.2 (1.2 to 1.2)	< 0.001
	White	29.6 (29.4 to 30.1)	2.5 (2.3 to 2.8)	1.7 (1.7 to 1.8)	< 0.001
Temperature from 21.00 h to 23.30 h	Metal	29.4 (29.1 to 29.7)	3.4 (3.1 to 3.7)	..	..
	Red.	28.4 (28.1 to 28.8)	2.8 (2.6 to 2.9)	1.0 (0.9 to 1.1)	< 0.001
	White	27.8 (27.4 to 28.3)	2.5 (2.3 to 2.7)	1.6 (1.5 to 1.7)	< 0.001
Temperature from 07.30 h to 20.30 h	Metal	34.0 (33.5 to 34.4)	-1.4 (-1.7 to -1.1)	..	..
	Red.	34.4 (34.0 to 34.9)	-2.5 (-3.1 to -1.8)	-0.4 (-0.4 to -0.5)	0.081
	White	33.1 (32.7 to 33.4)	-3.9 (-4.8 to 3.1)	0.9 (0.8 to 1.0)	< 0.001

The percentage of time each roof typology was comfortable varied at different times of the day and night (Figure 4.6). Before midnight, it was more comfortable in red-roofed houses (56% of the time, Odds ratio, OR=8.44, 95% CI=5.67-12.57, p<0.001) and white-roofed houses (87% time, OR=43.69, 95% CI=27.46-69.52, p<0.001), than bare metal-roofed houses (13% time). After midnight, all houses were comfortable over 80% of the time, however, red-roofed houses (98% of the time, OR, R=5.63, 95% CI=2.31-13.69, p<0.001) were more comfortable, and white-roofed houses (81% time, OR=0.47, 95% CI=0.03-0.75, p<0.001) less comfortable, because they were colder, than bare metal-roofed houses (90% time). During the day, all of the houses were comfortable less than 35% of the time. It was more comfortable inside red-roofed houses (25% of the time, OR=2.20, 95% CI=1.45-3.34, p<0.001) and white-roofed houses (34% time, OR=3.40, 95% CI=2.27-5.09, p<0.001) than bare metal-roofed houses (13% time). Overall, white-roofed houses were the most comfortable.

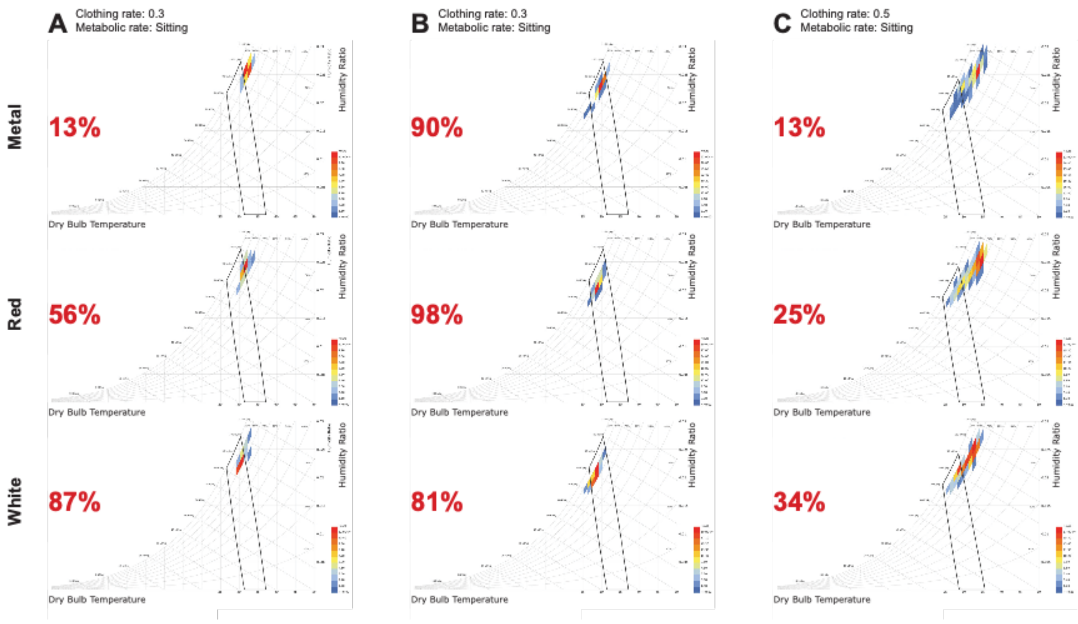

Figure 4. 6 Psychometric charts showing human comfort index of adults.
Where A = first part of the night 821.00 h to 23.30 h), B = second part of the night (00.00 h to 07.00 h) and C = day time (07.00 h to 20.30 h). Black polygon = values in which house is comfortable and percentages in red = readings that are classified as comfortable.

4.4.2 Roof costings

The cost of a white roof varies according to the quality of paint and which country one buys materials in (Figure 4.7). The cost of installing a metal roof in The Gambia, assuming the wooden roof frame was in place and there were no local transport costs would be 41.55 USD. A white-painted roof would cost 72.47 USD, including the price of metal sheets, and a roof coated with paint designed to be highly reflective would cost 136.24 USD. A fabric-coloured metal roof would cost 71.50 USD. Prices will vary widely across sub-Saharan Africa, according to the quality of the paint and the country of purchase. For example, 5 L of white gloss paint can vary in price between 6.76 USD and 13.53 USD in The Gambia and 15.13 USD and 48.68 USD in South Africa (prices accessed and converted to USD on 19th October 2020). In the Upper River Region, the median number of residents in a single room house is four (Q1=1, Q3=5, n=3,253 data collected from 13 Nov 2014 to 25 Mar 2015; M. Pinder, personal communication). Assuming this, a painted white-roof last 10 years, the cost per individual each year would be 1.81 USD.

	The Gambia (USD)	South Africa (USD)
A 	41.55	85.71
B 	72.47 (41.55 + 30.92)	154.03 (85.71 + 68.32)
C 	136.24 (41.55 + 94.69)	223.57 (85.71+ 137.86)
D 	71.50	92.17

Figure 4. 7 Roof costing with different technical specifications.
Where A = galvanized corrugated roof, B = galvanized corrugated roof with white coating, C = galvanized corrugated roof with white reflective coating and D = fabric-coloured roof. All prices were converted from Gambian Dalasis and South African Rands to USD by Morningstar at Google on 19th October 2020).

4.5 Discussion

The findings of this chapter show that painting a galvanised corrugated metal roof white made the house cooler during the day and night. Red roofs, simulating a rusty roof, were cooler at night, before midnight, than a house with a galvanised metal roof, but was as hot as a galvanised metal roof during the hottest time of the day in the late afternoon between 14.00 h and 17.00 h. The first hypothesis that coloured roof has effect on room temperature was correct; houses with white roofs were cooler than plain galvanised metal roofs at all times of day: 1.7 °C cooler from 21.00 h to 23.59 h, 1.6 °C cooler from 00.00 h to 05.59 h, and 0.9 °C cooler from 07:00 to 20:30, the hottest time of the day. The second hypothesis that roof colour enhances human comfort was false, houses with red roofs were not warmer than bare metal roofs during the day or night. Houses with red roofs were 1.2 °C cooler from 21.00 h to 23.59 h, 0.95 °C cooler from 00.00 h to 05.59 h, compared with galvanised metal roofed houses. Although red-roofed houses were 0.44 °C warmer than galvanised metal roofs during the hottest time of the day, this was not statistically significant.

A number of other studies have also found that white-roofed houses in the tropics are cooler than other roof colours [160,162,163]. Most of these studies, however, measured surface temperature of the roof or compared indoor temperature in houses with traditional and modern roofs. In Argentina, white-painted concrete roofs recorded average surface temperatures of 43.0 ºC, while terracotta-painted ones were 59.5 ºC [158]. Three years later, when the roofs were re-surveyed, surface temperatures were 47.5 ºC for white roofs and 63.5 ºC for terracotta roofs, suggesting that white paint did not deteriorate over this period and continued to be cooler compared with terracotta roofs. The white-roof coating also prevented deterioration of the roofing because it has higher solar reflectance and therefore reduced thermal expansion and contraction that causes cracks [163]. In The Dominican Republic, during the day, galvanized corrugated roofs painted white had surface temperatures of 33 ºC, whilst those painted dark red paint had temperature of 42 ºC [164]. In this experiment having a white-painted roof white increased the reflectance of light from 70 % to 80 % and probably increased the life of a roof by preventing rusting. In Ecuador, a study with 23 roofing samples commonly used for government-funded housing concluded an increase in the hours of comfort could be achieved by using higher solar reflectance roofing [161], findings consistent with our own study.

The analysis suggested that the number of paint layers applied to a roof did not affect indoor temperature. Galvanised metal roof sheets sold in The Gambia are thin, only 0.11 mm to 0.45 mm thick, and a layer of paint adds little insulation, therefore heat from solar radiation does not accumulate in the metal and is transferred rapidly to the surrounding air [164]. This aligns with the literature that describes an insulating material as one that has high thermal mass to reduce the maximum daytime temperature [163].

Indoor temperature decreased during the night following a similar pattern to that observed in previous studies [83,101]. Indoor temperatures were consistently warmer at night than outdoor temperatures. During the first and second parts of the night, on average galvanised metal roofed houses were 3.37 ºC and 3.41 ºC warmer, red-roofed houses 3.08 ºC and 2.78 ºC warmer, and white-roofed houses 2.51 ºC and 2.49 ºC warmer than outdoor temperatures. In marked contrast, during the day, the maximum indoor temperature in the galvanised metal-roof houses was 1.41 ºC cooler, red-roofed houses 2.47 ºC cooler and white-roofed houses was 3.93 ºC cooler than outdoors in the shade.

White-roofed houses were the least uncomfortable during the day, but were still too uncomfortable for most of the day, with indoor temperatures regularly exceeding 30°C. Nonetheless, before midnight they are the most comfortable houses with 87% of the evening being comfortable for people. Since this is the period when children [165] and adults [64] go to sleep, they most likely may use a bed-net more than those sleeping in houses with galvanised or red/rusted roofs. After midnight, people in white-roofed houses are slightly less comfortable than those in red-roofed houses as they would start to feel cold. Feeling cold though is easily solved by using a bedsheet, unlike being too hot which can only be reduced by increasing ventilation or sleeping with a damp towel. Lower indoor temperatures in poorly ventilated white-roofed houses will also reduce the concentration of carbon dioxide produced by people [69]. This is important since this gas is a major mosquito attractant, thus white-roofed houses may attract fewer malaria mosquitoes than houses with galvanised metal roofs. Painting a metal roof white is relatively cheap and would cost 41.55 USD and could last 5 - 10 years. As a malaria intervention it would cost 1.04 - 2.08 USD per person, which is favourable compared to the cost of ITNs (2.20 USD per person) and indoor residual spraying (6.70 USD per person) [166].

There are limitations to this study. First, the study was conducted in two experimental houses, thus only two different roof typologies could be tested simultaneously. Secondly, the study was conducted in single-room houses, which is not representative of all ethnic groups in The Gambia. In Mandinka villages, for example, most houses are multiple-roomed and built along a line [101], larger roof area could increase heat accumulation or disperse it. Also, the increase in buildings in the surroundings could prevent air flowing close to the house, cooling it down. Thirdly, the roof was painted with dark red paint to simulate the colour of a rusted roof. The change in roof colour, however, may not mimic the surface changes caused by rusting. Thus, a rough rusted roof may be hotter than the smoother red-painted roofs. Nonetheless, many houses in The Gambia are painted with red oxide paint, to prevent rusting and so our red roof is representative of a roof type common in the country. Fourthly, the houses were not inhabited at night, which would have raised indoor temperatures at night.

The increase in use of corrugate roofs throughout sub-Saharan Africa, reflects the need for cheap, durable, readily available materials for quick and simple construction. In contrast, traditional thatched roofs, although cheaper, are difficult to install well and need replacing every two to three years. Painting metal roofs requires specialist paints and could cost up to four times the price of normal wall paints but results in a surface that will not peal over time and can be applied on rusty surfaces. Today, corrugate roof sheets are available in different colours in the market at the same price as non-coated ones, but at almost twice the cost of galvanized metal sheets, which are the most popular roof choice in sub-Saharan Africa. The principal driver of the rainbow of different roof colours is one of satisfying personal choice, rather than being motivated by an effort to improve comfort levels indoors. To reduce indoor temperature and increase reflectance, roofs should be covered with reflective paint. The cost of which can double the cost of normal metal paint. Light-coloured roofs are likely to have high acceptance among local rural populations because corrugate roofs are perceived as a symbol of modernity and wealth. Further research is needed to assess acceptance of the colour, especially since light-coloured materials show dirt more readily than darker colours, and the possible association of white with a mourning colour in the region.

The findings of this chapter show that the colour of a roof impacts on indoor temperature in rural houses. Compared to a conventional, unpainted galvanised metal roof, a white-painted roof decreases indoor temperature both during the day and night. Importantly, in tropical areas a white-painted roof could make it more likely that residents would sleep under a bed-net at night and protect themselves from vector-borne diseases. A white-painted roof may last up to 10 years, increase the life span of the metal roof and, at a cost of 1.04 USD per person per year, is relatively cheap. Further cooling indoors could be achieved by installing a ceiling and increasing ventilation by installing screened windows on opposite walls [64]. Painting rural roofs with white paint will help make a dwelling more comfortable for the occupants and potentially increase bed-net use in hot humid countries.

Chapter 5. The importance of screened windows and doors to malaria mosquito house entry in The Gambia: pilot experimental studies.

5.1. Abstract

5.1.1. Background

Recent work in The Gambia showed that increasing the size of screened windows reduced the number of *Anopheles gambiae*, the principal malaria vector in sub-Saharan Africa, entering houses through gaps around the door. Here, we tested whether this phenomenon was caused by: (1) mosquitoes accumulating outside screening or (2) lower concentrations of carbon dioxide, a major mosquito attractant, indoors, or a combination of these.

5.1.2. Methods

Two identical experimental single-roomed houses were constructed in rural Gambia with mud block walls, a metal roof and two doors that had narrow slits above and below the doors to allow mosquitoes to enter. Two men slept under insecticide-treated nets in each house. Experiment 1 compared a house with two screened windows and one without windows. Mosquitoes were collected indoors using light traps and outdoors using electric grids positioned on windows. Experiment 2 compared a house with a screened door with one with a solid door. Mosquitoes were collected using light traps. Both experiments lasted 20 nights. Indoor climate and carbon dioxide were monitored using data loggers. Primary measurements were mean number of *An. gambiae s.l.* and mean temperature for each house modification. Multivariate analysis was carried out adjusting for confounders.

5.1.3. Findings

In experiment 1, multivariate analysis, showed house entry by *An. gambiae* declined by 38% (95% CI 23 to 50, p = < 0.001) with screened windows compared with houses without windows. Houses with screened windows were 17% cooler (95% CI = 7 to 25, p = 0.001) than houses with blocked windows from 21.00 to 23.30 h, and from 00.00 to 07.00 h (95% CI = 11 to 22, p= <0.001). In experiment 2, there were 76% fewer *An. gambiae* (95% CI 69 to 82, p = <0.001) in houses with screened doors compared with solid ones. Houses with screened doors were 42% (95% CI = 36 to 48, p= <0.001) cooler than the house with blocked doors from 21.00 h to 23.30 h, and 44% (95% CI = 40 to 48, p = <0.001) cooler from 00.00 to 07.00 h. Comfort levels before midnight were greater in screened houses than those with blocked entry elements.

5.1.4. Interpretation

Screened doors and windows reduce mosquito house entry indirectly, probably by reducing the concentration of host odours and diffusing these across a wider area than occurs in traditional houses. This finding supports using house screening for keeping the house cool and reducing malaria transmission in sub-Saharan Africa.

5.1.5. Funding

Global Challenges Research Fund, United Kingdom

5.2. Introduction

Malaria is a major cause of illness and is one of the greatest killers of children in sub-Saharan Africa [26,167] . In 2020, 95% of malaria cases and deaths occurred in sub-Saharan Africa [1]. The disease also restricts economic development and reduces the ability of individuals to work and attend school [26]. In 2002, the Disability Adjusted Life Years lost caused by malaria was 46,486,000. This disease not only causes work day losses within the working population but also increases the time that care providers give when taking care of the sick, losing school days or making the completeness of their other activities more challenging.

In sub-Saharan Africa, 79% of malaria transmission occurs indoors at night [100]. Preventing mosquitoes entering houses at night would be one way of reducing malaria transmission. Recent studies demonstrate that the structure of a building greatly affects the risk of house entry by mosquitoes, and, hence the transmission of malaria [84]. One important method of restricting mosquito house entry is screening all doors and windows in a house [84]. Not only is this a physical barrier to mosquito entry, it also makes the house cooler at night, making it more likely that people will sleep under an insecticide-treated bed-net at night [3]. A recent study in The Gambia made the surprising discovery that increasing the area of screened windows reduced the entry of mosquitoes into mosquito-porous houses, where the houses had narrow gaps above and below two external doors (Figure 5.1), to simulate badly-fitting doors common in Gambian villages. Compared with a house with small badly-fitting windows, having one large screened window reduced the number of *Anopheles gambiae* by 57%. This reduction increased to 95% when there were three large-screened windows in the house.

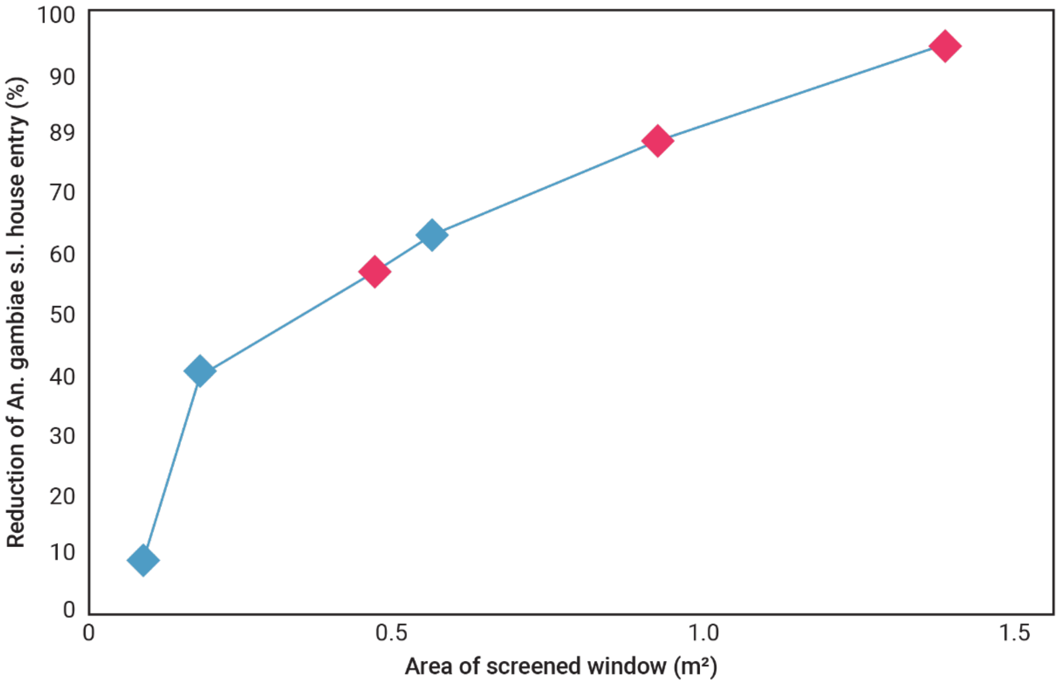

Figure 5. 1 Relationship between area of window screening and reduction in *An. gambiae* s.l. number indoors.
Light blue data points = small windows (Experiment 1) and pink data points = large windows (Experiment 2). Reductions are relative to the reference house in each experiment. Figure from Jatta, 2018 [69]

In this study three hypothesis were proposed to account for this behaviour. First, screening acts as a site of attraction, with mosquitoes attracted to host odours leaking from the screening, accumulating on the outside of the screening. Secondly, screening reduces indoor concentrations of host odours by a combination of increased ventilation and a cooler house reducing sweating and the production of host odours. Third, screening changes the shape of odour plumes emanating from a house, attracting fewer mosquitoes. Two experiments were carried out to explore whether hypotheses one and two were correct. In the first study we used four electric grids (one per window) to assess the number of mosquitoes attracted to screened windows. Electric grids had been used in previous experiments exploring the position of gravid females in relation to an aquatic habitat [168], but this is the first to use them for studying house entry. Of the different types of odours produced by humans, carbon dioxide (CO_2) is considered the most important [37], and for this reason measurement of this gas was undertaken in both experiments. Together, these studies were designed to better understand how screened windows and doors protected people in a house.

5.3. Methods

5.3.1. Study design

To test the hypotheses, two experiments were carried out in the field studies using two experimental houses in Wali Kunda field station (Figure 5.2), repeating the basic study design described by Jatta and colleagues [83], but, in addition to measuring indoor mosquito numbers and indoor temperature and relative humidity, indoor CO_2 concentrations were measured as well. In experiment 1, both houses had solid doors, one had screened windows and one had no windows. This experiment confirmed the findings of the experiments conducted during the first study, but in addition allowed the measurement of indoor CO_2 concentrations to test hypotheses one, two and three. Typologies were rotated between houses weekly and the experiment lasted 20 nights. In experiment 2, one house with solid doors was compared with one with screened doors, both doors had narrow slits top and bottom. If hypothesis 1 was correct, more mosquitoes would be collected in the house with screened doors than solid doors, since mosquitoes accumulating outside the screened door, attracted to odours from the door, would enter the house through the door gaps in larger numbers than houses with solid doors. Typology of the houses changed every other night for 20 nights.

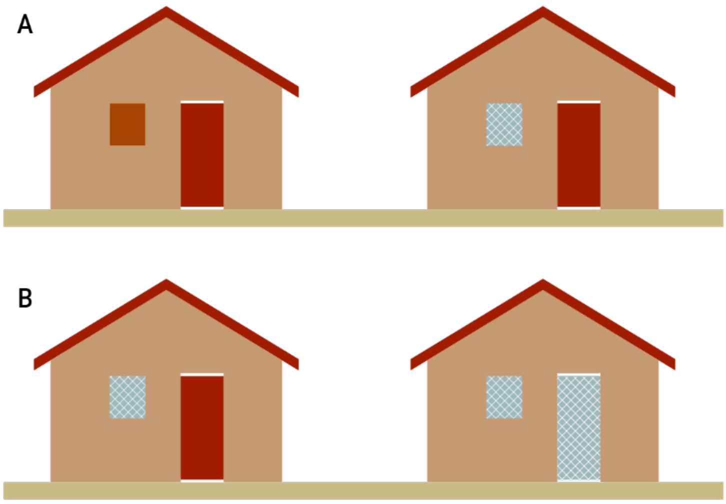

Figure 5. 2 Illustration of Experiments 1 (A) and 2 (B) comparing reference house (left) with intervention house (right).
White lines = narrow gaps in the doors and light blue squares and rectangles = screened windows and doors.

5.3.2. Study area

The study took place in 2019, in the grounds of the Medical Research Council's field station at Wali Kunda (N 13° 34"25', W 14° 55"28'). The site is situated on the south bank of the River Gambia and close to a large rice-cultivation area, in the Central River Region. The study was done during the rainy season, from June to October, when malaria transmission is high and people are most likely to sleep under an insecticide treated net (ITN).

5.3.3. Experimental houses

Field experiments were conducted during the rainy season, from 28th August to 11th November 2019 using two experimental mud-block houses with red-painted roofs, located 10 m apart from each other (Figure 5.3). The dimensions of the houses were the average size of single-roomed houses in The Gambia. The houses were 4.20 m by 4.20 m and 2.20 m high. Windows measured 0.65 m wide by 0.77 m high and were screened with plastic mesh (2 x 2 mm holes, Faura, San Isidro, Spain) with no insecticide treatment fitted in the inner side of the frame. Both houses had two windows next to the doors, located on opposite sides of the house facing north and south. The third door was replaced by a wall. Doors were 1.80 m high by 0.80 m wide with 20 mm gaps on top and bottom to replicate badly-fitting solid doors common in the villages. Each house was arranged with two single beds located parallel to one another on opposite walls to the doors.

Figure 5. 3 Experimental houses with one door and one window on the front and rear facades.

For the first experiment we compared houses with screened windows and no windows, the latter by blocking the window frame completely with plywood, 0.80 m wide x 0.70 m high x 18 mm thick, placed in the inner side of the window frame (Figure 5.5). Both house typologies had solid doors with 20 mm gaps above and below the doors. House modifications were rotated every two days and sleeper pairs rotated daily for 20 nights.

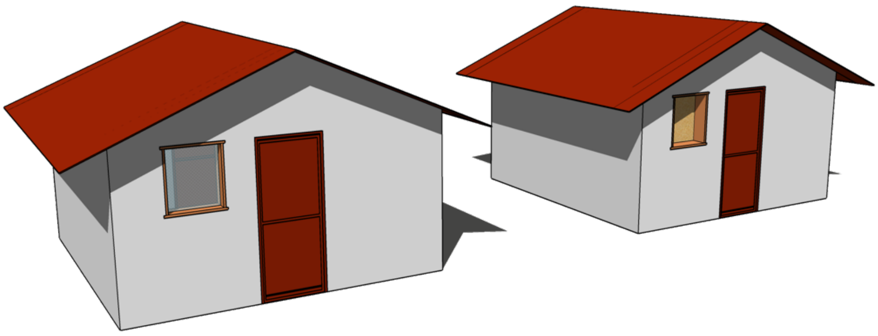

Figure 5. 4 Image showing both houses during Experiment 1.
One house with screened windows (left) and one control house with the window covered by a piece of plywood (right).

On the outer side of each window we placed a wooden frame with electrified wire [168]. Electric cables attached to the grid went inside the house to a transformer (spark box) that was connected to a 12 V car battery located on the floor of the house (Figure 4.6). The spark box provided a 400 V direct current into the grid and was connected at 21.00 h, when the sleepers went inside the houses, until 07.00 h the next morning. Double-sided sticky paper (HK Gardening, Zhejiang China) was placed at the bottom of each grid to collect dead mosquitoes that might fall from the grid's wires.

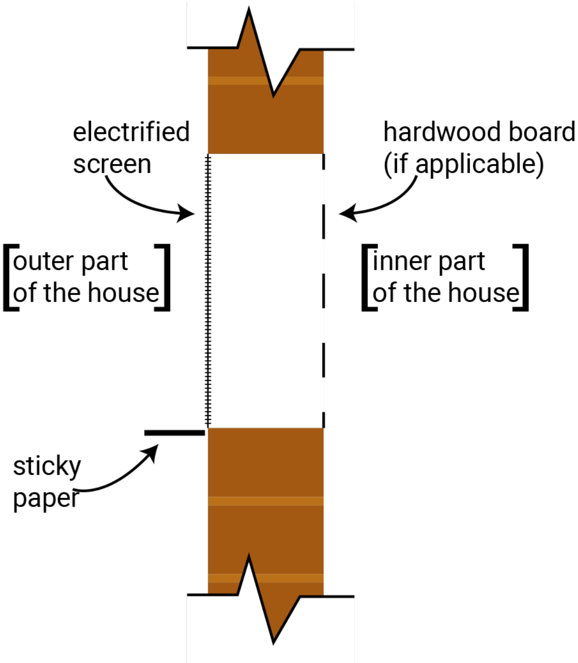

Figure 5. 5 Schematic detail section of the window and location of grids, screening and plywood.

For the second experiment a house with screened doors was compared with a house with solid doors. Both houses had screened windows and treatments were either screened or solid doors, with 20 mm slits above and below the doors (Figure 5.6). Screened doors had two mesh panels, 0.75 m wide and 0.60 m high. The total screening in the house with screened doors was 2.8 m^2 and solid doors was 1.02 m^2. Each door frame was fixed to the wall and the doors attached to the frame by two rising butt hinges. Treatments were rotated every two days following a replicated Latin Square design by lifting the doors and placing them in the hinges in the adjacent house. House modifications were rotated every two days and sleeper pairs rotated daily for 20 nights.

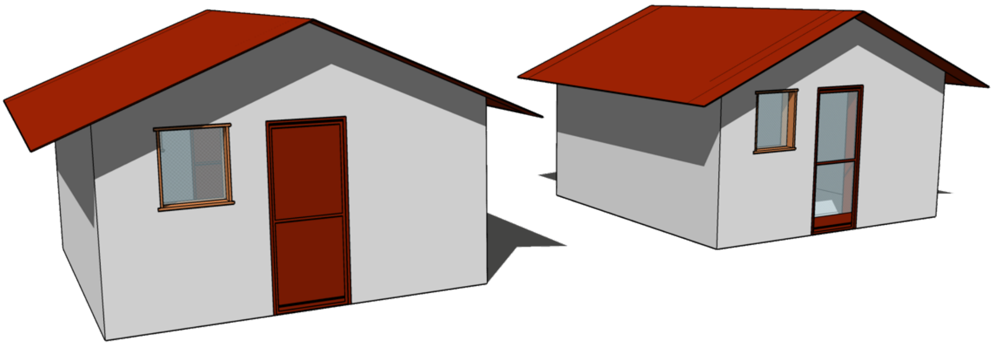

Figure 5. 6 Image showing both houses during Experiment 2.
One control house with solid doors (left) and the other house with screened windows (right).

5.3.4. Human Subjects

The study was explained to the study subjects in Mandinka, the local language, at a village meeting. Four healthy men over 15 years old living in Wali Kunda village, provided signed-witnessed consent. Sleepers participated during experiments 1 and 2 of this study. Before the first experimental session, volunteers slept in the houses for three consecutive nights to impregnate houses with human scent. Each night, each pair of volunteers slept in individual bamboo beds, with their heads closest to the southern door, under separate ITNs (Olyset Net, Permethrin, 1.30 m wide, 1.50 m high and 1.80 m in length, Sumitomo Chemicals, Japan). Volunteers slept in the houses for five nights a week for four weeks. i.e. 20 nights for each experiment. Two adult men slept on separate beds in each house under an ITN (Olyset, Sumitomo Chemical, Japan) from 21.00 h to 07.00 h.

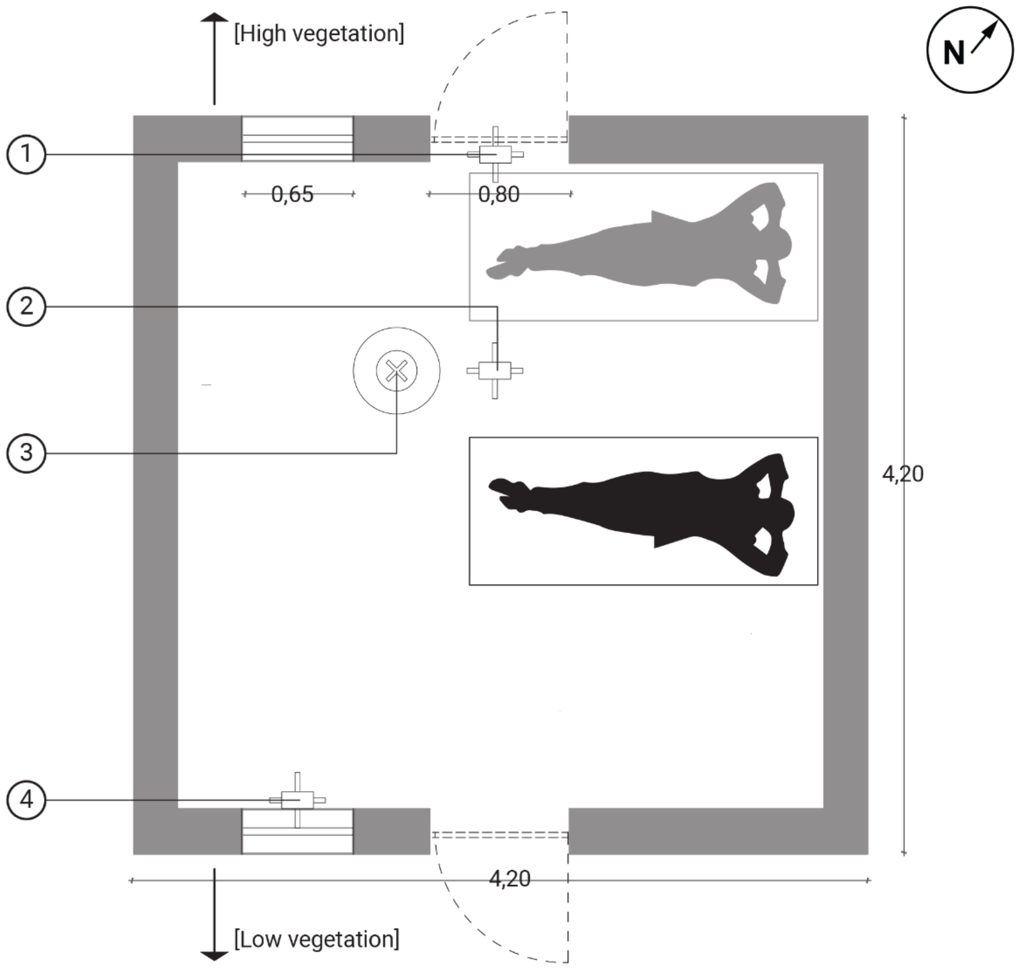

Figure 5. 7 House plan showing sleepers and data logger positions.
1 = carbon dioxide logger at door level, 2= temperature logger, 3=CDC light trap and D = carbon dioxide logger at window level.

5.3.4. Entomology

At the start of experiments 1 and 2, each typology was randomly allocated to one house position. For each experiment, Centers for Disease Control and Prevention (CDC) light traps (Model 512, John W. Hock Co., Gainesville, USA) located 1m above the ground and in between the two beds close to the bottom were used to sample mosquitoes indoors. Collected mosquitoes were killed by freezing, identified morphologically using established keys [16,129] and female *An. gambiae* s.l. identified to species by PCR [130–132].

5.3.5. Environmental measurements

Indoor temperature and humidity was measured every 30 min with data loggers (Tiny tag, TGU 4500, Gemini Data Loggers, Chichester, UK) and CO_2 concentrations every 30 sec with loggers (1% CO2 + Rh/T Data Logger GasLab, Florida, USA) in the houses. Temperature loggers were located in the centre of each room and 1 m from the floor. CO_2 loggers were located in between the two beds closer to the top of the beds and 1 m from the floor, on top of the back door (2.10 m high) and on top of the front window (2.10 m high) (Figure 4.8). Outdoor temperature and relative humidity were recorded with a data logger located in a Stevenson screen, with wind speed and direction recorded every 30 min by an automatic weather station (MiniMet, Skye Instruments, Llandrindod Wells, UK). Meteorological instruments were located midway between the two houses.

5.3.5. Outcomes

Primary outcomes were the mean indoor temperature, and the mean number of *An. gambiae* s.l./light trap/night for each house typology. Night-time temperature was analysed from 21.00 to 23.59 h, when adults in the study area go to bed and make a decision to sleep under a bed-net or not [3], and from 00.00 to 06.59 h, when most are asleep [64].

5.3.6. Statistical analyses

The sample size was estimated considering these experiments as pilot exercises, designed to inform future studies about sample sizes. For experiment 1 it was hypothesised that at least 66% more mosquitoes would be collected in a house with blocked windows compared to one with screened windows. In 2017 in nearby Wellingara village [3], a mean of 6.2 *An. gambiae*/night (standard deviation= 5.1) were collected in metal-roofed houses with no windows and badly-fitting doors. To detect a 66% reduction in mosquitoes killed by the grid on the house with screened windows at 5% level of significance, with 80% power would require 19 nights of observation, rounded up to 20 nights. In experiment 2 it was hypothesised that if mosquitoes are attracted to odours leaking from screening, at least 66% fewer *An. gambiae* will enter houses with screened windows and badly fitting solid doors, than a house with screened windows and screened doors. Thus in this experiment we thought it likely that screened doors would increase indoor mosquito densities, since if mosquitoes accumulated on the outside of the screening they would enter the building through the narrow slits above and below the doors. Since the calculation was the same as experiment 1, we also carried out this experiment for 20 nights.

The effect of house typology on indoor climate and mosquito house entry was assessed using generalized estimating equations (GEE), using a negative binomial model with a log link function for count data, whilst comparisons of indoor temperatures were made using linear regression. To assess the independent effect of house typology over time, fixed effects like house position and day were included in the model. The mean ratio is expressed as difference in estimated mosquito counts between the control house and intervention, while the protective efficacy is the effect estimate of the intervention. LadyBug software (LadyBug Products, Athol, ID, USA) was used to estimate the percentage of time occupants of various house typologies spent in the 'comfort zone' [169]. Chi-square test was used to look for trends in human comfort with increasing numbers of large-screened windows and for comparisons between typologies. Analyses, apart from psychrometric analysis, were done using Stata version 24 (StataCorp, College Station, TX, USA), except for chi-square calculations which were done with Epi Info version 3.01 (CDC, Atlanta, USA).

5.3.7. Ethics statement

The study was approved by the Gambia Government/Medical Research Council's joint ethics committee (11th July 2019) and the Department of Biosciences ethics committee, Durham University, UK (28th August 2019).

5.4. Results

5.4.1. Experiment 1: Screened windows vs no windows

A total of 6,095 mosquitoes were collected over 23 nights inside the houses, the three extra nights were the nights used for the houses to get human odours. Of these, 1,337 (21.9%) were female *An. gambiae* s.l., 4,608 (75.6%) female *Mansonia* spp., 62 (1.01%) female *Culex quinquefasciatus* and the rest other anophelines, *Aedes aegypti* and *Cx. thalassius*. Mosquitoes identified as *An. gambiae* s.l. were identified with PCR analysis: 29 % were *An. arabiensis* (35/120) and 71 % *An. coluzzii* (84/120).

Few mosquitoes were collected in the electric grids and the sticky paper on the exterior part of the windows. A total of 225 mosquitoes were collected over 23 nights. Of these, 7 (3 %) were female *An. gambiae* s.l., 203 (90 %) female *Mansonia spp*., 8 (4 %) female *Cx. quinquefasciatus* and the rest other anophelines and *Cx. thalassius*. Due to the small numbers of mosquitoes collected they were excluded from further analysis.

In this experiment, fewer *An. gambiae* entered the house with screened windows compared with houses with blocked windows (Figure 5.8). For other species of mosquito, there were similar numbers of mosquitoes entering both typologies of houses.

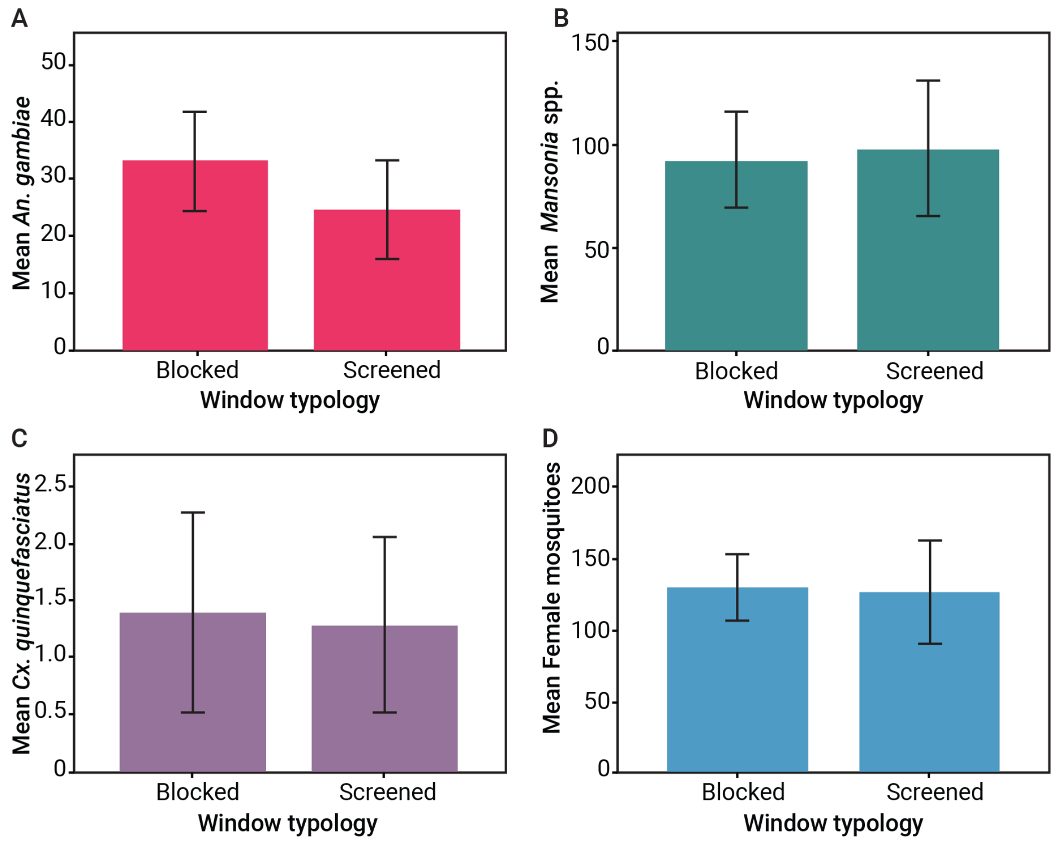

Figure 5. 8 Unadjusted mean mosquito house entry in houses with different windows (Experiment 1).
Where A = *An. gambiae*, B = *Mansonia* spp., C = *Cx. quinquefasciatus* and D = all mosquitoes. Error bars are 95 % confidence intervals.

The adjusted multivariate analysis demonstrated that 38 % (95 % CI 23 to 50 %) fewer *An. gambiae* entered houses with screened windows compared with a house without windows (Table 5.1). There was no difference in the number of *Cx. quinquefasciatus* or *Mansonia* spp. in the two treatment groups.

Table 5. 1 Mosquitoes collected from houses with and without screened windows and adjusted analysis.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals.

Type of window	No. collected	Dif. from control house (95% CIs)	Protective efficacy (95% CIs)	p value
Female *Anopheles gambiae*				
Blocked	763	Reference	..	..
Screened	567	0.62 (0.50 to 0.77)	- 38 % (23 to 50)	< 0.001
Female *Mansonia* spp.				
Blocked	2136	Reference	..	..
Screened	2269	1.03 (0.88 to 1.19)	+ 3 % (-19 to 12)	0.745
Female *Culex* spp.				
Blocked	28	Reference	..	..
Screened	26	0.87 (0.49 to 1.57)	- 13 % (-57 to 51)	0.652
All mosquitoes				
Blocked	2972	Reference	..	..
Screened	2898	0.94 (0.81 to 1.09)	- 6 % (-9 to 19)	0.433

Indoor temperatures declined from an average of 29.2 °C at 21.00 h to 26.9 °C at 07.00 h, but were always about 3° C warmer than outdoors (Figure 5.9). Univariate analysis showed no difference between the house with blocked windows (control) and the house with screened windows during the first part of the night (21.00 h to 23.30 h) and significant difference during the second part (Table 5.2). During the second part of the night (00.00 h to 07.00 h) there was a 17% (95% CI 11 to 22) reduction in the temperature of the house with screened windows compared with the control house (Table 5.2).

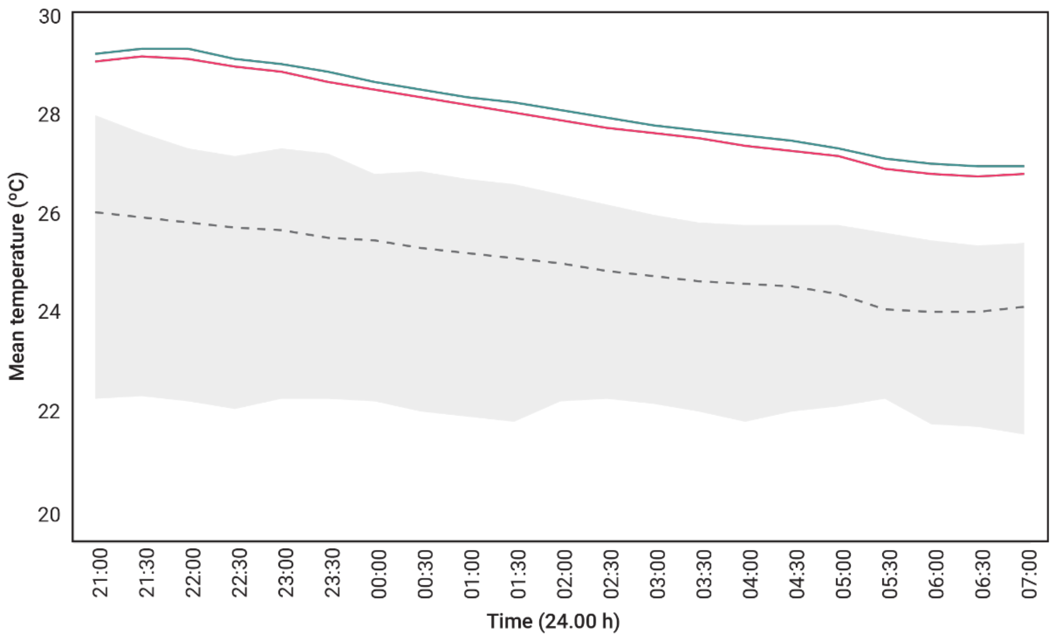

Figure 5. 9 Unadjusted indoor and outdoor temperatures in houses with different windows (Experiment 1).
Where gray area = minimum and maximum outdoor temperature levels, green line = house with blocked windows, pink line = house with screened windows and dashed black line = outside temperature.

Table 5. 2 Temperature and carbon dioxide means at different stages of the night from houses with and without screened windows and adjusted analysis.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals.

	Average temperature from 21.00 h to 23.30 h			Average temperature from 00.00 h to 07.00 h		
	Average (°C)	Difference from control house	p value	Average (°C)	Difference from control house	p value
Outdoors	25.8 (25.4 to 26.1)	..	..	24.7 (24.5 to 24.8)	..	..
Blocked window	29.2 (28.9 to 29.5)	Reference	..	27.7 (27.6 to 27.9)	Reference	..
Screened window	29.0 (28.9 to 29.2)	0.80 (0.75 to 0.93)	0.019	27.5 (27.5 to 27.6)	0.83 (0.78 to 0.89)	<0.001
	Average carbon dioxide from 21.00 h to 23.30 h			Average carbon dioxide from 00.00 h to 07.00 h		
	Average (ppm)	Difference from control house	p value	Average (ppm)	Difference from control house	p value
Blocked window	948 (939 to 957)	..	..	876 (873 to 878)	..	..
Screened window	894 (888 to 900)	0.43 (0.27 to 0.69)	0.001	828 (826 to 830)	0.41 (0.23 to 0.73)	0.003

Houses with blocked windows had higher carbon dioxide concentrations than those with screened windows (Figure 5.10). Loggers located in the centre of the room (A) and closer to the sleepers' heads (B) had higher recordings of carbon dioxide levels compared to the logger located near the end of the bed (C). In the adjusted analysis during the first half of the night, the house with screened windows had 57% (95% CI 31 to 73) less carbon dioxide concentration than the control house, this finding was of borderline significance. During the second part of the night the house with screened windows had 59% (95% CI 27 to 77) less carbon dioxide concentration than the control house (Table 5.2). Indoor concentrations of CO_2 rose above background levels shortly after two men entered each house at 21.00 h, to a maximum roughly one hour later, before declining gradually through the night, before a small rise around 05.00 h, one hour before the men left the houses (Figure 5.10). Indoor CO_2 concentrations were 152 ppm (95% CI 109-195 ppm, p<0.001) lower in screened-door houses than those with solid doors from 19.00 to 23.59 h (p = <0.001) and 120 ppm lower (95% CI 81-159 ppm, p = <0.001; table 3) from 00.00 to 05.59 h.

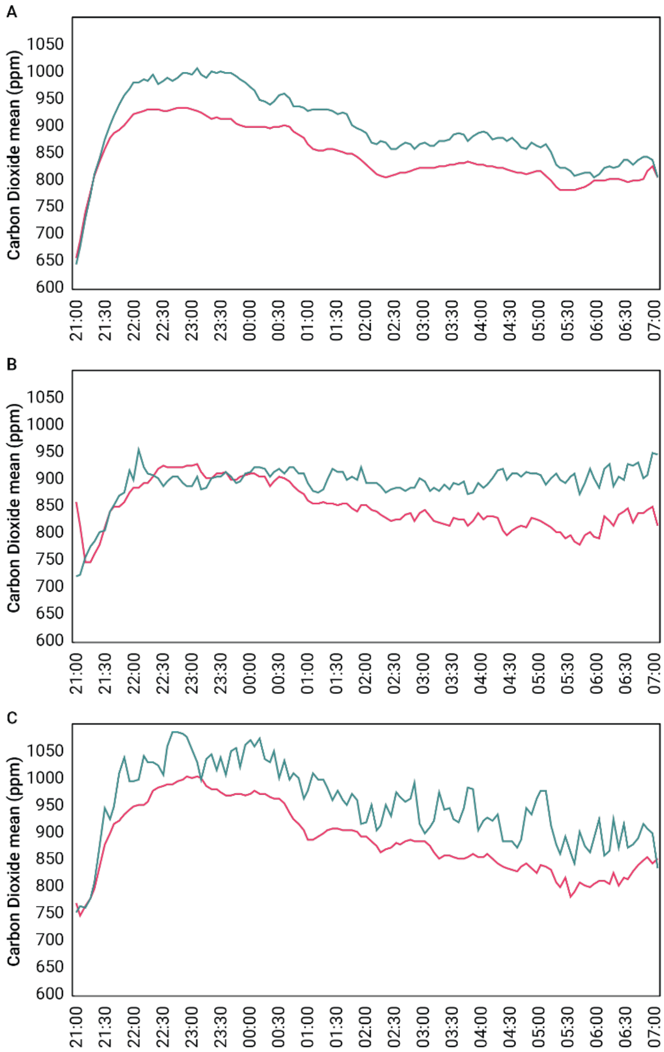

Figure 5. 10 Unadjusted carbon dioxide concentration in houses with and without screened windows.
Where A = loggers in the centre of the house (1 m above the floor), B = loggers on top of the front window (1.75 m above the floor), C = loggers on top of the northern door (1.75

above the floor), green line = house with blocked windows and pink line = house with screened windows.

5.4.2. Experiment 2: Screened doors vs solid doors

A total of 9,070 mosquitoes were collected in houses over 19 nights instead of 20 due a light trap malfunction on one night. Of these, 381 (4.2%) were female *An. gambiae* s.l., 8,550 (94.3%) female *Mansonia spp*., 62 (0.7%) female *Cx. quinquefasciatus* and the rest other anophelines, *Aedes aegypti* and *Cx. thalassius*. Mosquitoes identified as *An. gambiae* s.l. were identified with PCR analysis: 29 % were *An. arabiensis* (38/120) and 71 % *An. coluzzii* (81/120). Fewer *An. gambiae, Cx. quinquefasciatus*, *Mansonia spp*. and total mosquitoes entered the house with screened doors compared with the houses with solid doors (Figure 5.11).

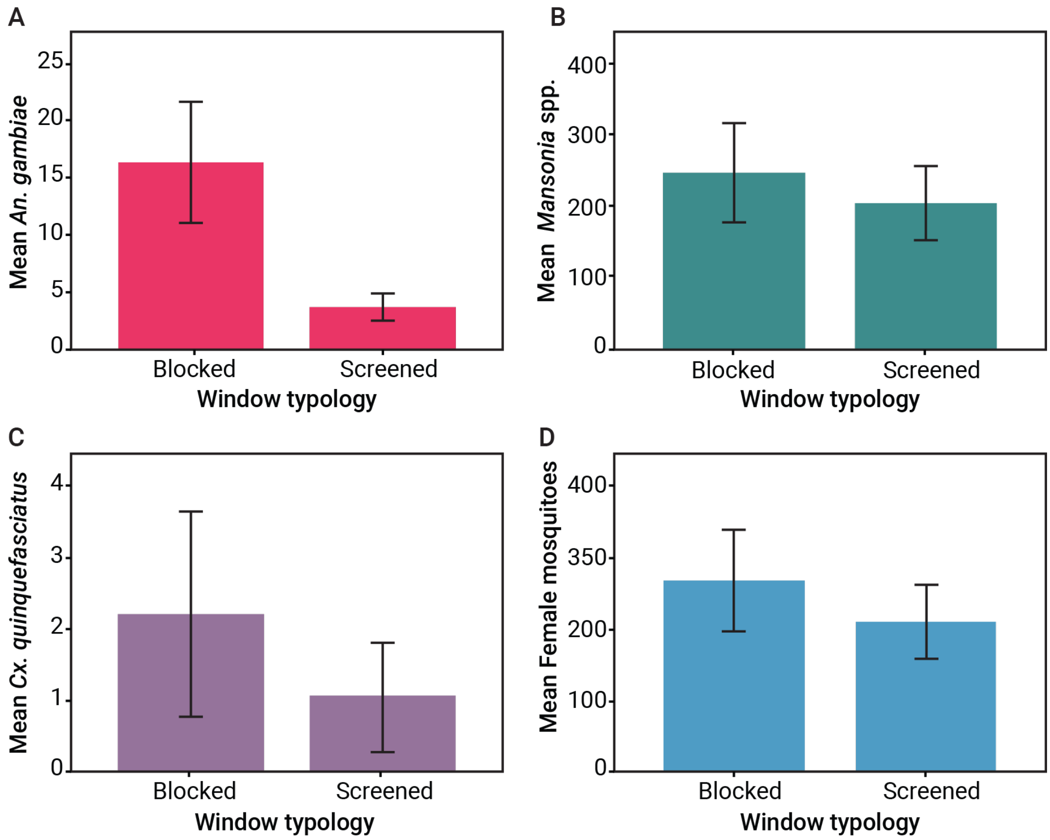

Figure 5. 11 Unadjusted mean mosquito house entry in houses with different doors (experiment 2).
Where A = *An. gambiae*, B = *Mansonia* spp., C = *Cx. quinquefasciatus* and D = all mosquitoes.

In the adjusted analysis, there were 76% (95% CI 69 to 82 %) fewer *An. gambiae* entering houses with badly-fitting screened doors compared with houses with badly-fitting solid doors (Table 5.3). With *Cx. quinquefasciatus* there was a 45% reduction (95% CI 14 to 65 %), with *Mansonia spp* catches a 18% (95% CI 0 to 32 %)

reduction. Overall, the total mosquitoes catches were 22% less (95% CI 6 to 35 %) in houses with screened doors compared to those with solid doors.

Table 5. 3 Mosquitoes collected from houses with badly-fitting screened doors and houses with badly-fitting solid doors and adjusted analysis.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals.

Type of door	No. collected	Dif. from control house (95% CIs)	Protective efficacy (95% CIs)	p value
Female *Anopheles gambiae*				
Solid	310	Reference	..	..
Screened	71	0.24 (0.18 to 0.31)	- 76 % (69 to 82)	< 0.001
Female *Mansonia* spp.				
Solid	4686	Reference	..	..
Screened	3864	0.82 (0.68 to 1.00)	- 18 % (0 to 32)	0.051
Female *Culex* spp.				
Solid	42	Reference	..	..
Screened	20	0.55 (0.35 to 0.86)	- 45 % (14 to 65)	0.009
All mosquitoes				
Solid	5090	Reference	..	..
Screened	3980	0.78 (0.65 to 0.94)	- 22 % (-6 to 35)	0.008

Indoor temperatures declined progressively through the night but were always roughly 2.5° C warmer than outside. (Figure 5.12). Houses with screened doors, however, were cooler than those with solid doors. Before midnight, the rate ratio was 42 % less (95% CI 36 to 48) in a house with screened doors compared to one with solid doors and 44% less (95% CI 40 to 48) after midnight (Table 5.4).

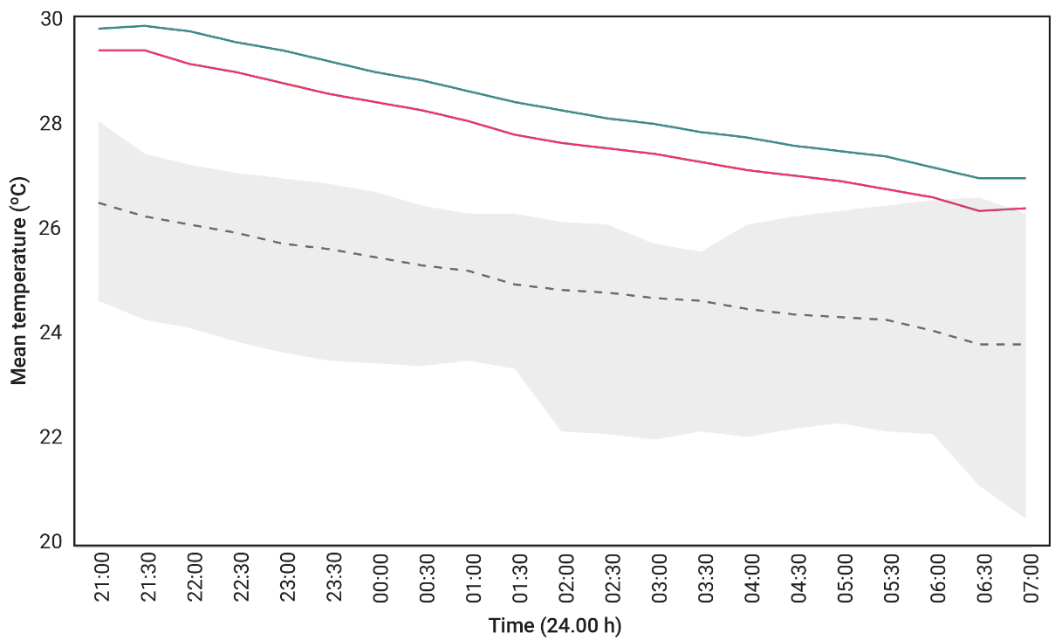

Figure 5. 12 Unadjusted mean indoor and outdoor temperatures in houses with different doors (experiment 2).
Where gray area = minimum and maximum outdoor temperature levels, blue line = house with solid doors, orange line = house with screened doors and dashes black line = outdoor temperature.

Table 5. 4 Temperature and carbon dioxide means at different stages of the night from houses with badly-fitting screened doors and houses badly-fitting solid doors and adjusted analysis.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals.

	Average temperature from 21.00 h to 23.30 h			Average temperature from 00.00 h to 07.00 h		
	Average (°C)	Difference from control house	p value	Average (°C)	Difference from control house	p value
Outdoors	26.0 (25.8 to 26.2)	··	··	24.6 (24.4 to 24.7)	··	··
Solid door	29.6 (29.4 to 29.7)	Reference	··	27.9 (27.8 to 28.0)	Reference	··
Screened door	29.0 (28.8 to 29.0)	0.58 (0.52 to 0.64)	<0.001	27.3 (27.3 to 27.3)	0.56 (0.52 to 0.60)	<0.001
	Average carbon dioxide from 21.00 h to 23.30 h			Average carbon dioxide from 00.00 h to 07.00 h		
	Average (ppm)	Difference from control house	p value	Average (ppm)	Difference from control house	p value
Solid door	810 (806 to 815)	··	··	748 (746 to 749)	··	··
Screened door	659 (657 to 660)	0.22 (0.15 to 0.32)	<0.001	630 (629 to 630)	0.31 (0.22 to 0.43)	<0.001

The highest concentrations of carbon dioxide were achieved approximately 30 min after the sleepers entered the houses and declined gradually during the night, before a small increase in concentrations starting around 06.00 h (Figure

4.13). Carbon dioxide measurements in the house with screened windows were between 600 and 700 ppm in the loggers located in the centre of the house and on top of the window. The logger located on top of the back door in the same house registered measurements ranging from 600 to 800 ppm. In the house with blocked windows all three loggers measured carbon dioxide measurements ranging from 600 to 850 ppm. In the adjusted analysis from 21.00 to 23.59 h, the house with screened doors had 78% (95% CI 68 to 85) less CO_2 concentration compared with the house with solid doors (Table 5.4). From midnight to 7.00 h, the reduction in CO_2 concentration was of 69% (95% CI 57 to 78).

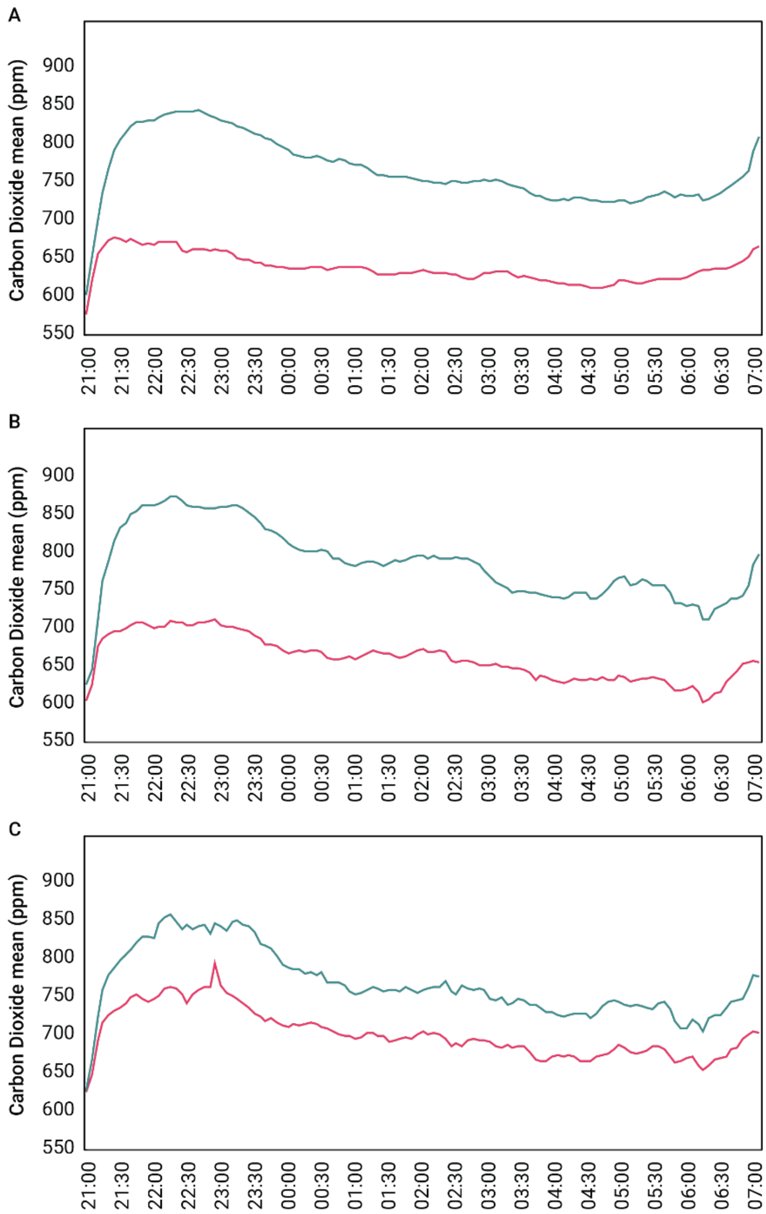

Figure 5. 13 Unadjusted mean carbon dioxide concentration in houses with badly-fitting screened doors and badly fitting solid doors.

Where A = loggers in the centre of the house, B = loggers on top of the front window, C = loggers on top of the northern door, green line = house with solid doors and pink line = house with screened doors.

5.5. Discussion

Screening entry points like windows, doors and eaves have proved an effective method to keep mosquitoes outside the house [84]. Keeping the vector out would also mean a decrease in malaria transmission, since *An. gambiae* s.l., the major malaria vector in sub-Saharan Africa, is endophilic [3,100]. Moreover, screening the house would provide similar protection to all household members, even those not using a bed-net. In this study in addition to screened entry points acting as a barrier to mosquitoes, the dimension and location of the screened area also had an impact on indoor mosquito density. Two screened windows on opposite sides (1 m^2 of screened area) reduced *An. gambiae* entry numbers by 38% compared with no windows. Whilst two screened doors and two screened windows on opposite sides (3.88 m^2 of screened area) reduced the numbers further to 76%, compared with a house with two screened windows and solid doors. The reduction in biting obtained by screening windows and doors are equivalent to that of an insecticide-treated net where reductions of biting of 54 to 82 % occur [170]. Smaller reductions occurred in numbers of *Mansonia spp.* (18%), *Cx. quinquefasciatus* (45%) and total mosquitoes (22%) entering the houses by adding screened doors. The location of the screening area is important since windows located on opposite sides will facilitate cross ventilation, whereas screened area on adjacent walls will not be as effective. These findings support the earlier study by Jatta and co-workers [69] who showed a progressive decline in *An. gambiae* house entry with increasing area of screened window to a maximum of 1.5 m^2 of window screening with three large windows.

In this study, indoor temperature decreased during the night following the ambient temperature pattern. Compared with the house with blocked windows, the house with screened windows was 0.2° C cooler during the whole night (21.00 h to 07.00 h). With the addition of screened doors, the temperature dropped by a further 0.6° C during the night compared with the reference house. These findings are similar to those in a neighbouring village where the addition of two large-screened windows temperature decreased indoor temperature by 0.4 °C compared with the control house [69]. These changes in general indoor temperature between the different typologies of houses were perceived by the sleepers, who mentioned the house with blocked windows as being “too hot” and the house with screened doors as the “most comfortable” during informal conversations.

CO_2 levels during both experiments rose rapidly after the men entered the houses. This pattern was consistent with circadian rhythms [171] , where people’s temperature and carbon dioxide levels are high around 21.00 h and fall down along the night. Following the circadian rhythms pattern, during experiment 2 carbon dioxide levels started to increase again around 06.30 h, when the body starts to warm up in preparation for the day [171]. However, this increase was not present during experiment 1. This change in the pattern might be caused by alterations in the sleeping rhythms and, therefore, in the CO_2 levels due the change of the sleepers environment. Because CO_2 is used by mosquitoes to find their blood source [37], the lower concentrations in the houses with screened doors might contribute to the decrease of indoor mosquito levels.

The first hypothesis explored whether screening acted as decoy, attracting more mosquitoes to the screened surfaces and preventing them to locate the gaps or slits. If the first hypothesis was correct, more mosquitoes would have been collected in the house with screened doors than those with solid doors, since mosquitoes would accumulate close to the screening, making it more likely that they would enter the house through the slits above and below the doors. This was not the case, since more mosquitoes were collected in houses with solid doors than those with screened doors. Therefore, the hypothesis that mosquitoes accumulate in large numbers outside screening is rejected.

The second hypothesis suggested that screening entry points would reduce host odours emanating from the house as a result of a decrease in temperature and an improved crossed ventilation. The findings supported this hypothesis since CO_2 levels were lower in screened houses than those that are unscreened. Furthermore, this decrease was larger with screening doors compared with screening windows, suggesting that increased area of screening reduces CO_2 levels. Presumably, the lower concentrations of CO_2 in screened houses makes it more difficult for mosquitoes to locate a human to feed on. While diurnal mosquitoes rely on shapes for orientation, nocturnal ones guide themselves through odour plumes [37].

There are two limitations to this study. Firstly, the study was conducted in only two houses, built as single-room separated houses. In local villages most houses are multiple-roomed and built closer together [101]. Secondly, adults usually go to bed later at night than in our study and doors are continuously opened and closed before midnight [64]. It is not known how human behaviour will impact the protection afforded by house screening.

The findings of this chapter show that the number of malaria mosquitoes entering a house declines with increasing screened area. This results from the reduction in levels of carbon dioxide used by mosquitoes to locate the house. Mosquitoes are less likely to find a person sleeping in a house with screened doors and windows than from a house with solid badly-fitting doors. Having two screened doors on opposite sides of the house is roughly equivalent to the protection of a ITN. This study is relevant to understanding how mosquitoes approach and enter the house. We suggest that screening windows and doors will increase the willingness of people to use a bed-net, created a combined and more effective protection strategy. Screening doors and windows is likely to reduce mosquito house entry and keep the house cooler.

Chapter 6. Effect of passive and active ventilation on human comfort and malaria mosquito-house entry: an experimental study in rural Gambia

6.1 Abstract

6.1.1 Background

Insecticide-treated nets (ITN) are the principal malaria control tool in sub-Saharan Africa, however, they are often not used when it is too hot. Designing cheap ways to ventilate and cool a house should increase ITN compliance. Here we assess whether passive or active ventilation methods can cool a bedroom at night and reduce house entry of malaria mosquitoes in rural Gambia.

6.1.2 Methods

Two identical metal-roofed experimental houses with badly-fitting doors and screened windows were used: one ventilated and one unventilated, serving as a reference. In the passive ventilation experiment, a transparent solar chimney was fitted to the external wall of the house. Heated by sunlight, warm air rises up the chimney pulling in cooler air from within the house, creating a cooling air current indoors. In the active ventilation experiment, an electric-ceiling fan was installed in both houses, with only one used each night. In each house, two men slept under separate ITNs. Measurements were made for four nights each week, with house treatments changed weekly for eight weeks (n=32 nights). Indoor evaporation, temperature, relative humidity, carbon dioxide and wind speed were monitored and mosquitoes collected using light traps.

6.1.3 Findings

Anopheles gambiae s.l. house entry declined by 26 % (95 % CI 20-31) with a solar chimney and by 91 % (95 % CI 90-92) with a ceiling fan compared to the reference houses. Number of *Mansonia* spp., however, increased in a house with a solar chimney, but not an operating fan, compared with the reference house. Although there were no differences in indoor nightly temperature between intervention and control house, nightly evaporation in a house with the solar chimney was 61 % higher (95 % CI 61 to 61%) and a house with a fan operating 319 % higher (95 % CI 319 to 319) than a reference house. Solar chimneys reduced indoor carbon dioxide levels by 28 % (95 % CI 18 to 36) and ceiling fans by 19 % (95% CI 11 to 27) from 00.00-07.00 h compared with the reference house.

6.1.4 Interpretation

Passive and active ventilation reduced female *An. gambiae* house entry, by increasing airflow in the house, which reduces dioxide levels indoors making it more

difficult for a female mosquito to locate a blood meal from outside a house. Improved ventilation in houses may make it more likely that people will use a bed-net at night and reduce house entry by malaria vectors, helping to reduce malaria transmission.

6.1.5. Funding

Tropical Infectious Disease Consortium, Liverpool School of Tropical Medicine, United Kingdom.

6.2 Introduction

In sub-Saharan Africa, most rural houses are built from mud [98,101] and concrete, both materials with a high thermal mass, making them hot at night [83,101]. These structures are made even hotter if the roofs are made from metal [58]. Consequently, at night, when people go to bed, the room is often uncomfortably hot [65,83], making it less likely that people will protect themselves from malaria by sleeping under an insecticide-treated net (ITN) [3,172], which further restricts airflow and potential cooling [123]. This is especially important considering that roughly 80 % of malaria transmission in the region occurs indoors and at night [100,173]. Simple and cheap methods are needed to keep houses cool, especially at night, whilst keeping out malaria mosquitoes and without using energy expensive cooling devices like air conditioners.

Ventilation, by adding at least two large-screened windows in opposite walls of a single-room house is one method by which rural homes can be cooled, replacing hot, static indoor air with cooler air flow from outdoors [69]. Improving ventilation indoors also reduces the levels of carbon dioxide in a room both directly by removing the gas from the room and indirectly by reducing the temperature of the room and therefore lowering the need for the human body to cool [69]. Lowering carbon dioxide concentrations indoors will make it more difficult for a mosquito to locate and feed on a person, since this gas is the major long distance attractant for malaria mosquitoes [37].

For houses without electricity, the hypothesis was that solar chimneys, a type of passive ventilation, would reduce indoor temperature in single-roomed houses. Briefly, a solar chimney is a device positioned on the sunny side of the house. The chimney, heated by direct sunlight, warms the air in the chimney, causing it to rise through an inlet in the bottom of the wall and out of the top of the chimney, dragging in cooler air from the room, increasing ventilation indoors and cooling the room (Figure 6.1). Passive ventilation has been used for centuries in hot climates, including wind catcher towers in Iran [174], Malay traditional houses design [175] and, in the natural world, termite mounds [176]. Today, with increasing global temperatures, people are looking at passive ventilation strategies as a way of having comfortable living and working environments without excessive energy consumption and expenditure [177,178]. In Venezuela, a solar chimney reduced indoor temperature at the hottest time of the day by 2-4 ºC, compared with outdoor temperature [179]. Whilst, in Colombia, a solar chimney combined with an ground-air heat exchanger, a underground duct designed to move cooler air into the house after hot air has been expelled by the solar chimney, reduced indoor temperature by 1 ºC between 10:00 h and 16:00 h compared to the control house [180]. One alternative cooling strategy is to use active ventilation. For houses with electricity, bedrooms can be made cooler by using a fan that increases airflow across the body, helping to keep the body cool. Although ceiling fans are common in modern houses in the tropics and sub-tropics, studies on their effect on indoor temperature are scarce. In Singapore, office workers found it more comfortable at 26 ºC with fan-assisted air movement compared with 23 ºC without fans [181]. Although there is anecdotal evidence that strong ceiling fans prevent mosquitoes flying, this has not to our knowledge, been tested in the field.

The present study assessed whether passive and active ventilation would make a typical rural Gambian house more comfortable at night and reduce mosquito-house entry, by lowering indoor carbon dioxide concentrations, making it less likely that a malaria mosquito would enter a house. Constructing houses that are cooler and have fewer mosquitoes could contribute to a reduction in malaria transmission by cooling down spaces, making them more comfortable and people more willing to sleep under a bed-net [3] or enter their houses earlier at night (Figure 6.2). Furthermore, a cooler house would reduce the carbon dioxide produced by its occupants decreasing the odour plume that guides mosquitoes.

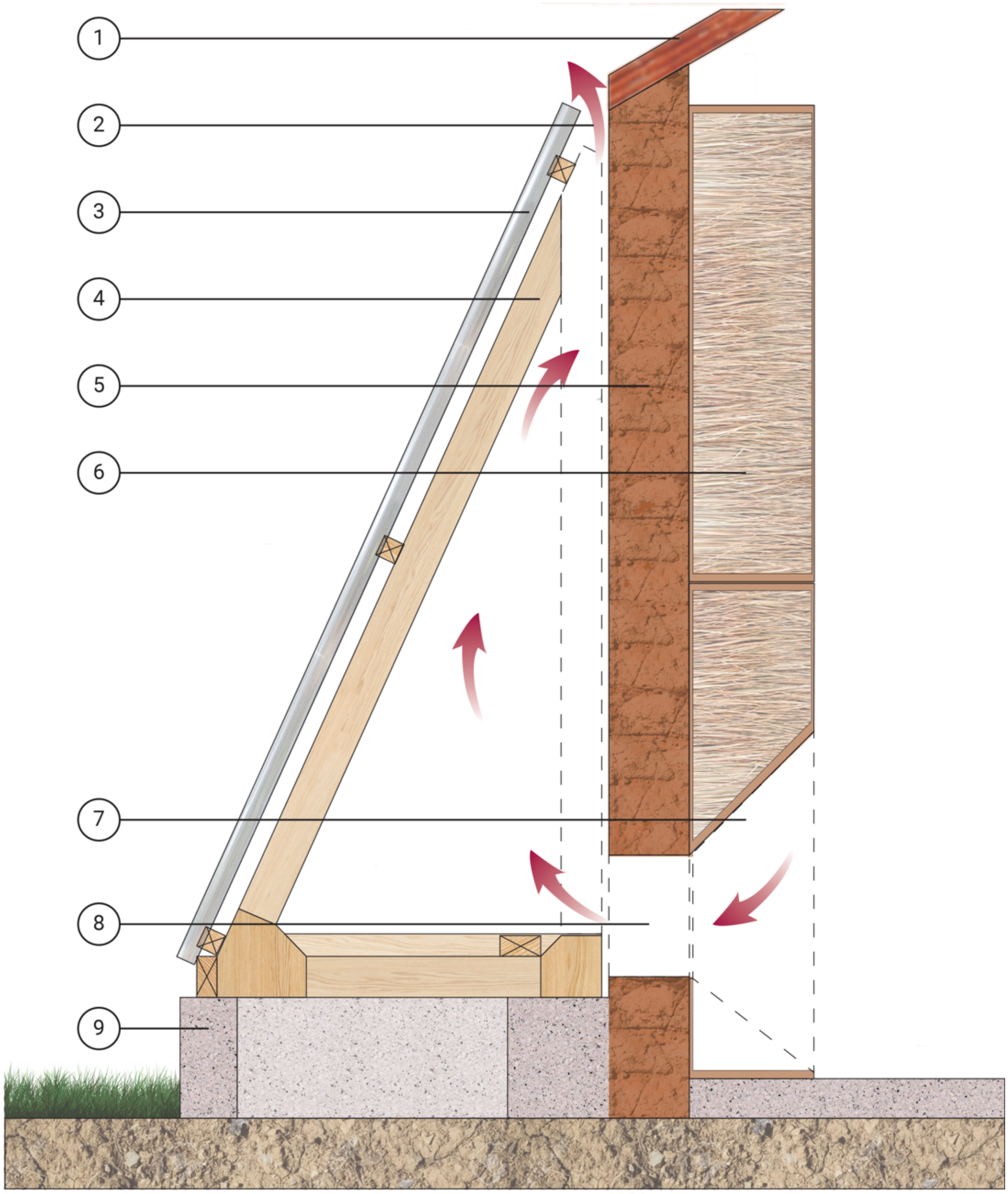

Figure 6. 1 Air movement through the solar chimney.
Where 1 = corrugated metal roof at wall level, 2 = hot air outlet, 3 = transparent corrugated metal sheet, 4 = wood frame, 5 = mud-brick wall (painted black on the outside), 6 = thatch inside plywood frames, 7 = plywood isolation frame, 8 = wall hole to allow air flow, 9 = concrete plinth and red arrows showing circulation of hot air. Dotter lines represent section elements that are not coloured for better understanding.

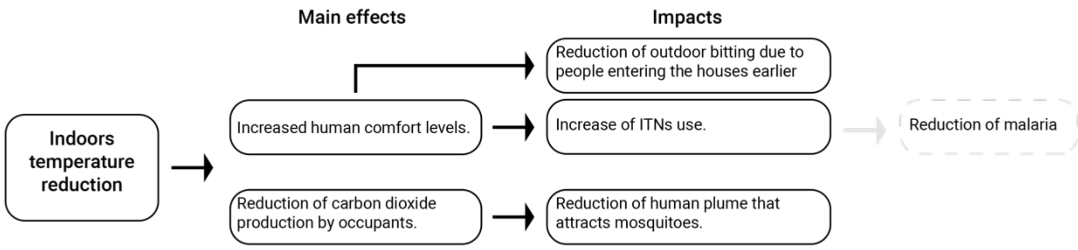

Figure 6. 2 Flow chart showing the effects and impacts of reducing indoor temperatures.
Dashed grey line showing possible effects.

6.3 Methods

6.3.1 Study design

This was an experimental study using two identical single-roomed experimental houses, each occupied by two adults. We conducted two experiments, comparing; (1) a house with a solar chimney and one without and (2) a house with a ceiling fan in operation and one not operating. Each experiment lasted 32 nights. In both experiments, house treatments were rotated every four nights. The initial allocation of treatment or control was random. Sleeper pairs were rotated nightly between houses for the duration of the experiment.

6.3.2 Study area

The study was conducted in Wali Kunda field station (N 13° 34’’25′, W 14° 55’’28′), located in the Central River Region, The Gambia. This is an area of flat Sudanese savanna, located close to a large rice-cultivated area. The study took place in 2021 during the rainy season, from July 23rd to October 24th, when numbers of *Anopheles gambiae*, the primary malaria vector, are greatest [83].

6.3.3 Experimental houses

Two experimental houses were used as described previously [123]. Briefly, both houses were the average size of single-roomed houses in the Central River Region of The Gambia. Houses were 4.20 m by 4.20 m in floor area, with walls 2.20 m high and 10.0 m apart. They were constructed from sun-baked mud-blocks and corrugated metal roofs with no eave gaps. Each house had two 1.80 m high and 0.80 m wide doors located in the north and south-facing walls of the house (Figure 6.3). Each door had narrow slits, each 20 x 800 mm, above and below the door, to simulate badly-fitting doors, common in the region, and to allow mosquitoes to enter the building. The houses had two 0.65 m high and 0.65 m wide screened windows (Polyester netting, 2 x 2 mm holes, Faura, San Isidro, Spain) located on the west façade of the house at 1.20 m from the ground. Each house had two beds, located parallel to one another on opposite walls, leaving a free space between them and connecting both doors.

Figure 6. 3 Experimental house with solar chimney on east-facing wall.

6.3.4 Solar chimney

A panelled solar chimney was built on the east-facing façade of the experimental houses to maximise solar radiation (Figure 6.3). It was a lean-to structure made of two 2.15 m panels and two 0.80 m triangular lateral panels. Each module had a timber frame (2.15 x 1.70 m) supporting 1 m x 2.4 m x 6 mm clear corrugated polycarbonate panels (Suntuf, Doncaster, UK). Panels were fixed on a concrete base (0.30 m high and 0.30 m wide) which had four slits (0.08 by 0.04 m) on the longest side to prevent rainwater accumulating during a heavy downpour. The panels were sealed on the frame using silicon sealant (Transparent Acetci Silicone Sealant, INGCO, Ghana) to prevent hot air leakage. At the top of the solar chimney there was a 30 mm gap between the panels and wall to allow hot air to leave the house. The outside wall on which the solar chimney was fixed was painted with matt black paint (Black paint, National Paints Factories, Dubai) to increase heating within the solar chimney. There were four rectangular holes, made in the base of the wall with the solar chimney, each 0.19 m x 0.37 m in area, 0.20 m above the floor. Each hole was made by removing a single mud brick and replacing it with a 12 mm plywood frame to support the wall while the experiment was taking place. The holes were covered with pieces of 12 mm plywood when the house was acting as control. On the internal face of the wall with the solar chimney we built a 0.30 m wide insulation layer made with eight plywood frames (0.95 m by 1.17 m on top and 0.95 m by 1.22 m at the bottom) filled with thatch to prevent the wall radiating heat into the room. The frames at the bottom of the wall had holes that allowed air movement from the room into the solar chimney (Figure 6.1).

6.3.5 Ceiling fan

One ceiling fan (F-56MZ2 56" Ceiling Fan 220 Volts, Panasonic, Japan) with 1.42 m blades and a diameter of 1.40 m was installed in each house and powered by 220 V mains electricity. Each fan was positioned in the centre of each room, anchored to a steel beam, 2 m above the floor. At 21:00 h one of the fans was switched on at the highest speed of 341 revolutions per minute and switched off at 07:00 h the next day.

6.3.6 Human subjects

The study was explained in a community meeting with male villagers in Mandinka, their local language. Four healthy males over 18 years old provided signed-witnessed consent and were hired to sleep four nights a week for the duration of the study. Women were excluded from the study due to cultural and religious reasons. Every night each pair of men slept, with their heads pointing north-west, under insecticide-treated nets (Olyset Net, Sumitomo Chemicals, Japan) 1.3 m wide x 1.8 m long x 1.5 m high, from 21.00 h to 07.00 h the following morning. Two field assistants were posted outside the experimental huts throughout the nights to assist the sleepers if they needed to briefly leave the house during the night and to make sure the men were sleeping under the bed-nets. Each pair of sleepers were rotated each night so that at the end of the experiment each pair had slept 16 nights in each one of the experimental houses.

6.3.7 Entomology

Mosquitoes were collected indoors using CDC light traps (Centers for Disease Control and Prevention, Miniature light trap model 512, US John W. Hock Ltd, Gainsville, USA) working from 21:00 h to 07:00 h. After collection, any mosquitoes still alive were knocked down in a -20° freezer and identified using standard morphological identification keys [16,129]. Members of the *An. gambiae* complex were identified using polymerase chain reaction [130–132].

6.3.8 Environmental measurements

Indoor temperature and relative humidity were measured for the duration of the study every 30 min in each hut using one data logger (Tiny Tag, TGU 4500), positioned in the centre of the room, 1 m above the floor and inside the solar chimney, 1 m above the floor of the house. Evaporation was measured nightly with a Piche evaporimeter (Casella, Sycamore, USA) located 1.20 m from the floor in the middle of the room hanging from the roof structure. Carbon dioxide was recorded every 30 sec from 21:00 h to 07:00 h each experimental night, with a data logger (1% CO2 + Rh/T Data Logger GasLab) located between the beds, near the head of the bed, 1.2 m above the floor (Figure 6.4). Indoor air speed was for a period of two hours in the house without chimney and the house with chimney with an 0.15 to 1.0 m/s air speed logger (HOBO T-DCI-F300-1x3 Sensor, HOBO, Bourne, MA; USA).

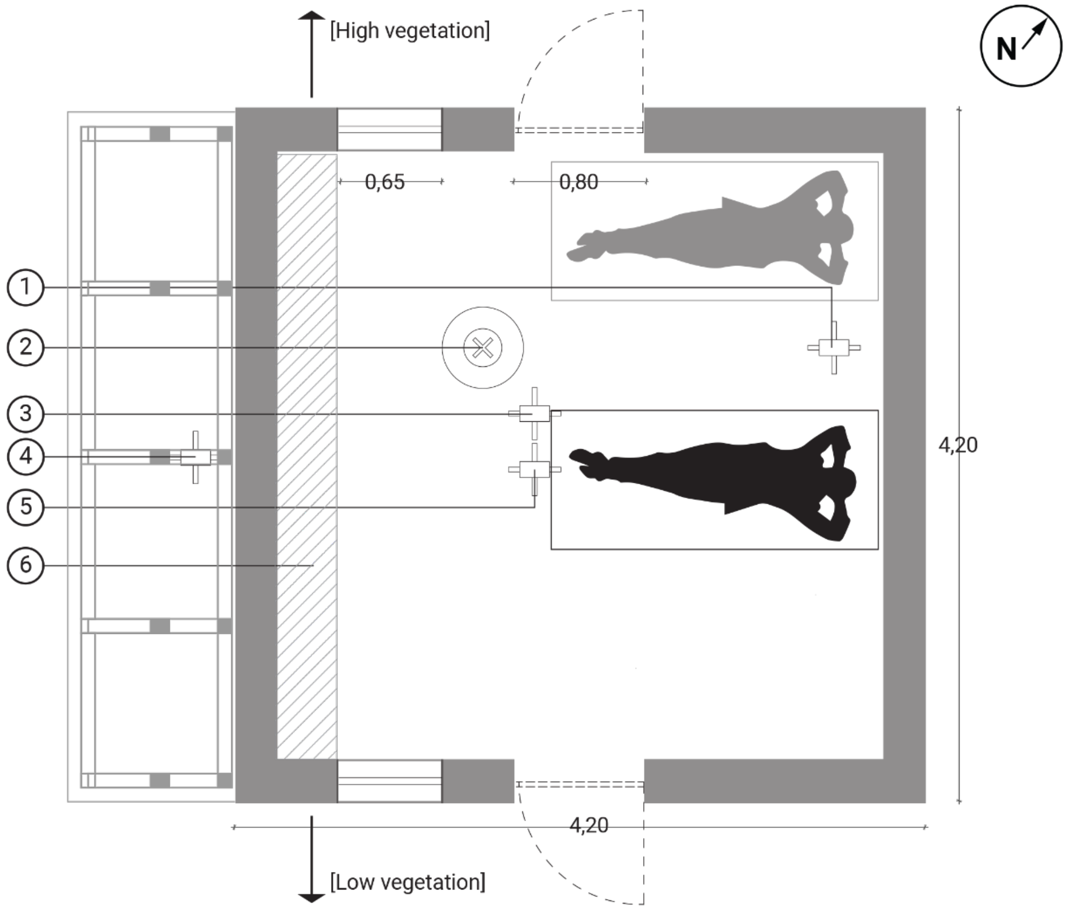

Figure 6. 4 Position of solar chimney and data loggers in experimental houses.
1 = carbon dioxide logger, 2 = CDC light trap, 3 = indoor temperature logger, 4 = chimney temperature logger, 5 = evaporimeter and 6 = isolation boxes.

Outdoor temperature and relative humidity were recorded every 30 min and carbon dioxide every 30 sec with a data logger (Tiny tag, TGU 4500 and 1% CO2 + Rh/T Data Logger GasLab) installed in a Stevenson screen positioned midway between the two experimental houses. Outdoor wind speed and wind direction were recorded with an automatic weather station (MiniMet, Skye Instruments, Llandrindod Wells, UK) every 30 min, located 10 m apart from the back façade and between houses.

6.3.9 Cost of intervention

Costs of building the two interventions were estimated. Costs were extracted from study records and were recorded in the currency of expenditure (Great Britain Pounds or Gambian dalasi, GMD). Costs were converted to United States Dollar (USD) using the mean exchange rate for the study period (June 29th, 2021) of 1 GMD = 0.019571 USD and 1 GBP = 1.3844 USD. Materials purchased for the chimney's construction were locally available in Banjul and transported to Wali Kunda.

6.3.10 Statistical analysis

The primary outcome was the indoor density of *An. gambiae* s.l.. The sample size was estimated via simulation based on a previous experiment done in the same area in 2018, where the mean number of *An. gambiae* s.l. collected in metal-roofed houses with two windows and badly-fitting solid and screened doors was 29.3 *An. gambiae*/night (standard deviation= 20.1). To detect a 50% reduction in mosquitoes caught in the house with improved ventilation, at the 5% level of significance, with 80% power would require 31 nights of collection. The same number of nights was considered sufficient show a significant difference in the other main outcomes. We conducted each experiment for 32 nights. Temperature and relative humidity measurements were analysed for two periods, from 21.00 h to 23.50 h, the time most people go to bed and decide whether to use a net or not, and from 00.00 h to 07.00 h, when they are asleep. [64] Evaporation indoors and indoor carbon dioxide levels were measured from 21.30 h to 07.00 h.

For the main analyses we used IBM SPSS Statistics 27 (IBM Corp., Armonk, NY, USA). We assessed the effect of house treatment on indoor climate and mosquito house entry using generalised estimating equations, using a normal distribution with identity link for continuous variables (i.e. temperature, relative humidity, evaporation and carbon dioxide), and a negative binomial model with a log link function for mosquito count data. Mosquito collections were presented as means with 95 % confidence intervals and analysed separately for each major taxon. In addition to house treatment, we included house position, sleepers' pair and night in the model as fixed effects. We used protective efficacy (1 – mean ratio x 100) to express the intervention effect estimate. This analysis allowed us to evaluate the independent effect of house treatment in each experiment, similar to what has been used in clinical trials and biomedical longitudinal studies [133]. Evaporation was calculated nightly for each house by subtracting the level of water recorded at 07.00 h from that recorded at 19.30 h. We used polar plots to depict the direction and strength of the wind during the day and night.

6.3.11 Ethics statement

The study was approved by The Gambia Government and Medical Research Council's Joint Ethics Committee (Reference: 17949, May 27, 2020), the Liverpool

School of Tropical Medicine (Research Protocol 19-111, 16 January 2020) and the Department of Biosciences Ethics committee, Durham University, UK (June 24, 2020).

6.4 Findings - Solar chimney (passive ventilation)

6.4.1 Entomology

A total of 2,558 female mosquitoes were collected in the light traps during the study, of which 10 % (246/2558) were *An. gambiae* s.l., 88 % (2239/2558) *Mansonia* spp., 1 % (25/2558) *Culex* spp. and the rest were other anophelines and *Aedes aegypti* (Appendix 3). Specimens identified as female *An. gambiae* were identified by PCR analysis as *An. coluzzii* (73 %, 22/30) and *An. arabiensis* (27 %, 8/30) in the control house and as *An. coluzzii* (67 %, 20/30), *An. arabiensis* (23 %, 7/30) and inconclusive (10 %, 3/30) in the house with the solar chimney installed.

Unadjusted analysis showed mean nightly female *An. gambiae* numbers of 3.6 (95 % CI 2.2 to 4.9) in the house with solar chimney and of 4.1 (95 % CI 2.8 to 5.4) in the control house (Figure 6.5). For *Mansonia* spp. mean average number in the house with solar chimney was 38.5 (95 % CI 26.0 to 50.9) and 31.5 (95 % CI 20.7 to 42.3) in the control house. All female anopheline and culicine mosquitoes had an average of 43.3 (95 % CI 29.9 to 56.8) in the house with solar chimney and of 36.6 (95% CI 25.2 to 48.0) in the control house.

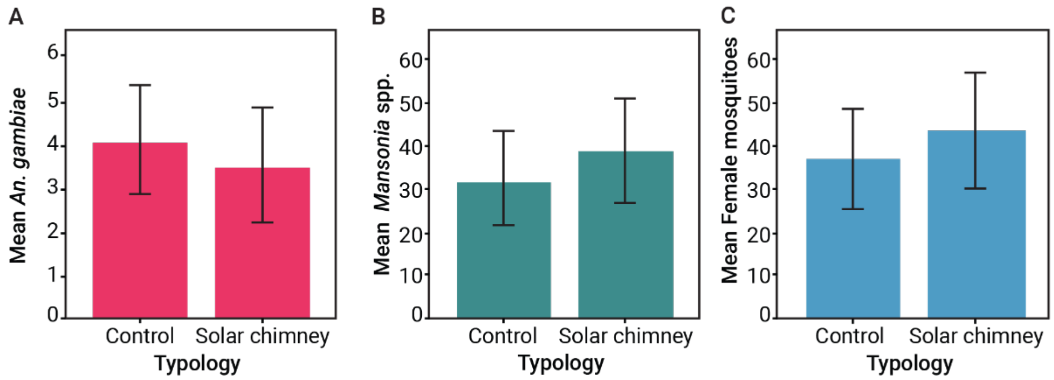

Figure 6. 5 Unadjusted mean mosquito numbers per night recorded during the Solar chimney experiment.
Where A = female *An. gambiae*, B = *Mansonia* spp. and C = all female anophelines and culicinae mosquitoes.

Adjusted analysis for confounders (house number, sleeper pair, night number) showed fewer *An. gambiae* in the solar-chimney house compared to the house without the chimney with a 26% reduction (95 % CI 20-31, p = < 0.001; Table 6.1). In contrast, *Mansonia* spp. increased by 28 % (95 % CI 28-29, p = < 0.001) and female mosquitoes by 21 % (95 % CI 20-21, p = < 0.001) in the house with the solar chimney compared to the house without one.

Table 6. 1 Female mosquitoes collected from houses with and without solar chimney and adjusted analysis.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals.

Typology	No. collected	Mean/night (95% CIs)	Dif. from control house (95% CIs)	Protective efficacy (95% CIs)	p value
Female *Anopheles gambiae*					
Control	132	4.1 (2.8 to 5.4)	Reference	..	..
Chimney	114	3.6 (2.2 to 4.9)	0.74 (0.69 to 0.81)	26 % (20 to 31)	< 0.001
Female *Mansonia* spp.					
Control	2491	31.5 (20.7 to 42.3)	Reference	..	..
Chimney	978	38.5 (26.0 to 50.9)	1.28 (1.28 to 1.29)	- 28 % (-28 to -29)	< 0.001
All mosquitoes					
Control	2638	36.6 (25.3 to 48.0)	Reference	..	..
Chimney	1032	43.3 (29.9 to 56.8)	1.21 (1.20 to 1.21)	- 21 % (-20 to -21)	< 0.001

6.4.2 Environmental measurements

Between 07.00 h and 20.30 h the average temperature in the house with the solar chimney was 30.5 ºC and 30.4 ºC in the control house, roughly 1 ºC and 1.2 ºC lower than outdoor levels (Figure 6.6, Table 6.2). During the day, the chimney had a mean temperature of 35.1 ºC, 4.6 ºC higher than the mean of the indoor temperature of both houses and 3.5 ºC higher than the outside average for the same period. Around 18:30 h the chimney stopped being warmer than the houses, a trend that was maintained until around 07.30 h. Between 21.00 h and 23.30 h, unadjusted average temperature inside the house with the solar chimney installed was 29.6 ºC and 29.5 ºC inside the control house, 3.5 ºC and 3.4 ºC higher compared to outdoor levels (Figure 6.6). The mean temperature inside the solar chimney from 21.00 h to 23.59 h was 28.3 ºC, 1.2 ºC lower compared to inside house levels but 2.2. ºC higher than outdoor levels. Between 00.00 h and 07.00 h the average temperature in both houses was 28.0 ºC, 3.2 ºC higher than outdoors. During the second part of the night the chimney unadjusted average temperature was 26.9 ºC, 1.1 ºC lower than inside the houses and 2.1 ºC higher than outdoors.

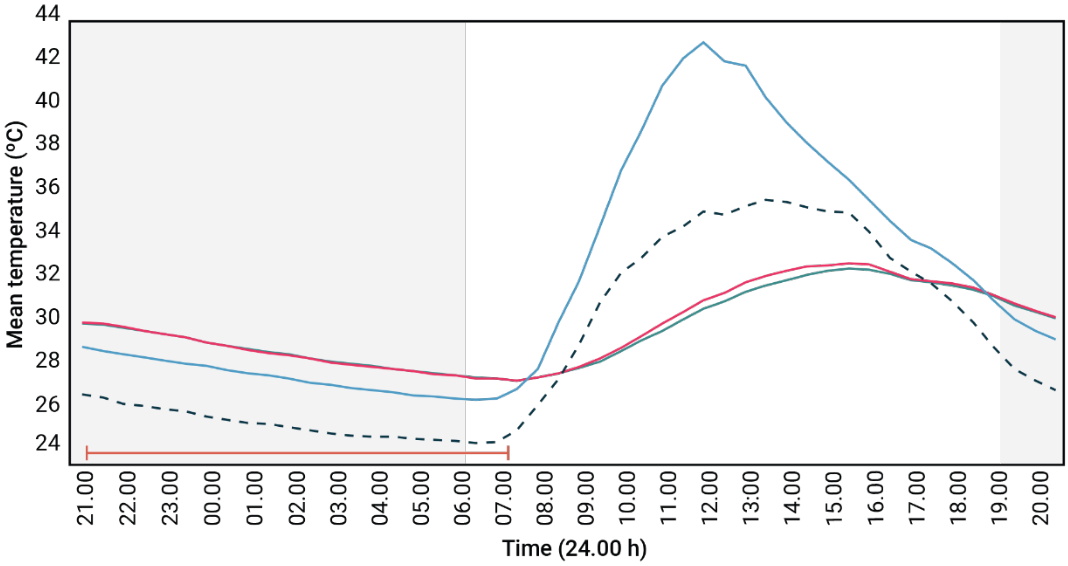

Figure 6. 6 Unadjusted mean indoor and outdoor temperatures recorded during Solar chimney experiment.
Green line = indoor temperature in control hut, pink line = indoor temperature in house with solar chimney, light blue line = temperature inside the solar chimney, dotted line = mean outdoor temperature, red line = experimental night duration and grey section = night time.

Mean indoor temperature in a house with the solar chimney was similar to a reference house during the night (Table 6.2). During the day, however, a house with a solar chimney was slightly hotter than the reference house, although this was of borderline significance. Relative humidity levels were similar between house types.

Table 6. 2 Average outdoor and indoor temperature, relative humidity and carbon dioxide concentrations in houses with and without a solar chimney and adjusted analysis.

Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals. Carbon dioxide was not recorded between 07ñ00 h and 21.00 h as the houses were unoccupied.

	Average temperature from 21.00 h to 23.30 h			Average temperature from 00.00 h to 07.00 h			Average temperature from 07.30 h to 20.30 h		
	Average (ºC)	Difference from control house	p value	Average (ºC)	Difference from control house	p value	Average (ºC)	Difference from control house	p value
Outdoors	26.1 (25.8 to 26.3)	··	··	24.8 (24.7 to 24.9)	··	··	31.6 (31.3 to 31.9)	··	··
Control	29.5 (29.3 to 29.7)	Reference	··	28.0 (27.9 to 28.1)	Reference	··	30.4 (30.2 to 30.5)	Reference	··
Chimney	29.6 (29.3 to 29.8)	1.03 (0.82 to 1.29)	0.791	28.0 (27.8 to 28.1)	0.99 (0.93 to 1.05)	0.761	30.5 (30.4 to 30.7)	1.22 (1.00 to 1.50)	0.053

	Average relative humidity from 21.00 h to 23.30 h			Average relative humidity from 00.00 h to 07.00 h			Average relative humidity from 21.00 h to 23.30 h		
	Average (%)	Difference from control house	p value	Average (%)	Difference from control house	p value	Average (%)	Difference from control house	p value
Outdoors	92.9 (91.5 to 94.3)	··	··	96.7 (96.3 to 97.1)	··	··	70.9 (69.8 to 72.1)	··	··
Control	75.1 (74.1 to 76.1)	Reference	··	77.0 (76.6 to 77.4)	Reference	··	71.0 (70.5 to 71.6)	Reference	··
Chimney	74.9 (73.9 to 75.8)	0.76 (0.27 to 2.15)	0.606	77.2 (76.8 to 77.6)	1.18 (0.95 to 1.46)	0.140	70.7 (70.1 to 71.2)	0.67 (0.33 to 1.36)	0.268

	Average carbon dioxide from 21.00 h to 23.30 h			Average carbon dioxide from 00.00 h to 07.00 h			Average carbon dioxide from 21.00 h to 23.30 h		
	Average (ppm)	Difference from control house	p value	Average (ppm)	Difference from control house	p value	Average (ppm)	Difference from control house	p value
Outdoors	555 (539 to 572)	··	··	546 (539 to 554)	··	··	··	··	··
Control	689 (673 to 706)	Reference	··	689 (679 to 699)	Reference	··	··	··	··
Chimney	667 (649 to 686)	0.84 (0.72 to 0.98)	0.026	644 (635 to 652)	0.72 (0.64 to 0.82)	< 0.001	··	··	··

Indoor evaporation was higher at night (21.00 h to 07.00 h) in a house with a solar chimney (mean 1.9 ml evaporated, 95 % CI 1.5 to 2.2) compared to one without (mean 1.4 ml, 95 % CI 1.0 to 1.8; Table 6.3). Analysis adjusting for confounders, evaporation in the house with the solar chimney was 61 % (95 % CI 61 to 61) higher than a house without a solar chimney. Wind speed and direction analysis showed most of the wind was coming from the North-West during the night (Appendix 4).

Table 6. 3 Indoor evaporation during both experiments.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals.

Solar Chimney				Ceiling fans			
Typology	**Mean/night (95% CIs)**	**Difference from control house**	**p value**	**Typology**	**Mean/night (95% CIs)**	**Difference from control house**	**p value**
Control	1.4 (1.0 to 1.8)	Reference	··	Control (fan off)	1.3 (0.9 to 1.8)	Reference	··
Chimney	1.9 (1.5 to 2.2)	1.61 (1.61 to 1.61)	< 0.001	Fan operating	2.6 (2.2 to 3.1)	4.19 (4.19 to 4.19)	< 0.001

Carbon dioxide levels increased immediately the sleepers entered the experimental houses to a peak around 22.00 h. Thereafter, carbon dioxide levels slowly declined before rising sharply after 06.30 h (Figure 6.7). There was a lower carbon dioxide concentration in a house with solar chimney than a house without a solar chimney in both parts of the night. The carbon dioxide concentration was 138 ppm higher in the control house than outdoor levels, whilst it was 105 ppm higher in the house with the solar chimney compared with outdoors. In the adjusted analysis, before midnight there was 16 % (95% CI 2 to 28) less carbon dioxide in the house with solar chimney compared with the control house, whilst it was 28% less (95 % CI 18 to 36) after midnight (Table 6.2). Analysis for the whole night showed 21 % (95 % CI 9 to 32, p = 0.002) less carbon dioxide concentration in the house with the solar chimney compared with a house without a chimney.

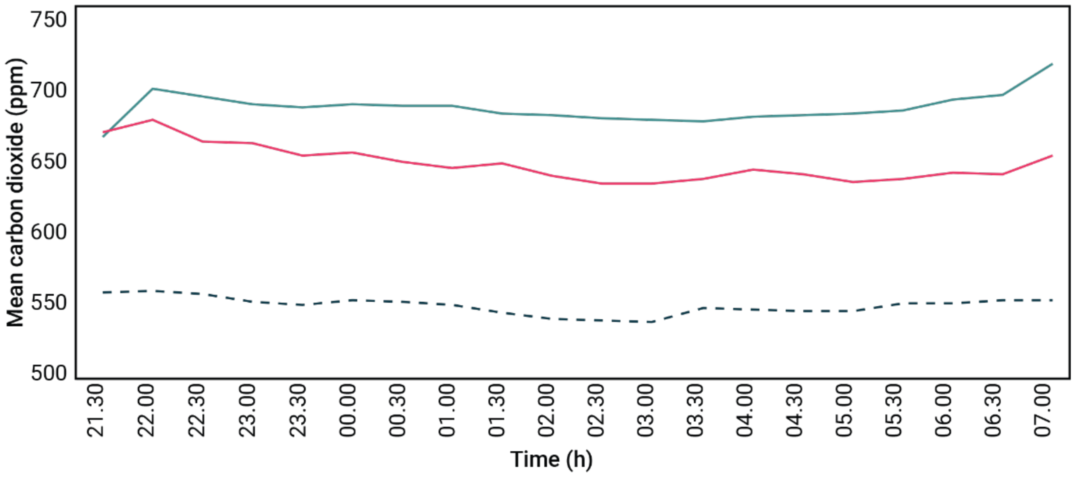

Figure 6. 7 Unadjusted mean indoor and outdoor night-time carbon dioxide levels recorded during the solar chimney experiment.
Where turquoise line = control house, orange line = house with solar chimney and dotter line = outdoor levels.

6.4.3 Cost of intervention

Installing a solar chimney in a traditional 4.20 by 4.20 single-roomed house a solar chimney with wooden structure and polycarbonate would cost 517.2 USD.

6.5 Findings - Ceiling fans (active ventilation)

6.5.1 Entomology

A total of 3,670 female mosquitoes were collected during the ceiling fan study, of which, 3.8 % (138/3670) were *An. gambiae* s.l., 94.5 % (3469/3670) *Mansonia* spp., 0.5 % (19/3670) *Culex* spp. and the rest were other anophelines and *Ae. aegypti* (Appendix 3). Specimens identified as female *An. gambiae* were identified by PCR analysis as *An. coluzzii* (80 %, 24/30), *An. arabiensis* (17 %, 5/30) and *An. gambiae* s.s./*coluzzii* hybrids (3 %, 1/30) in the house with the fan off and as *An. coluzzii* (83 %, 25/30), *An. arabiensis* (10 %, 3/30) and *An. gambiae* s.s./coluzzii (3 %, 1/30) and inconclusive (3 %, 1/30) in the house with the working fan.

Unadjusted analysis of the mean number of female *An. gambiae*, *Mansonia* spp. and female mosquitoes showed that there were fewer mosquitoes in a house with a ceiling fan turned on compared with a house where the fan was turned off (Figure 6.8). Mean numbers of female *An. gambiae* s.l. in the house with the working fan was 1.1 (95 % CI 0.3-1.8) and in the house with the fan turned off it was 3.5 (95 % CI 2.1-4.9). Mean numbers of *Mansonia* spp. in the house with working fan was 27.9 (95 % CI 14.6-41.2) while in the control house was 85.9 (95 % CI 55.3-116.5). Mean numbers of female anophelines and culicines in the house with working fan was 29.5 (95 % CI 15.5-43.5) and 91.0 (95 % CI 59.6-122.4) in the control house.

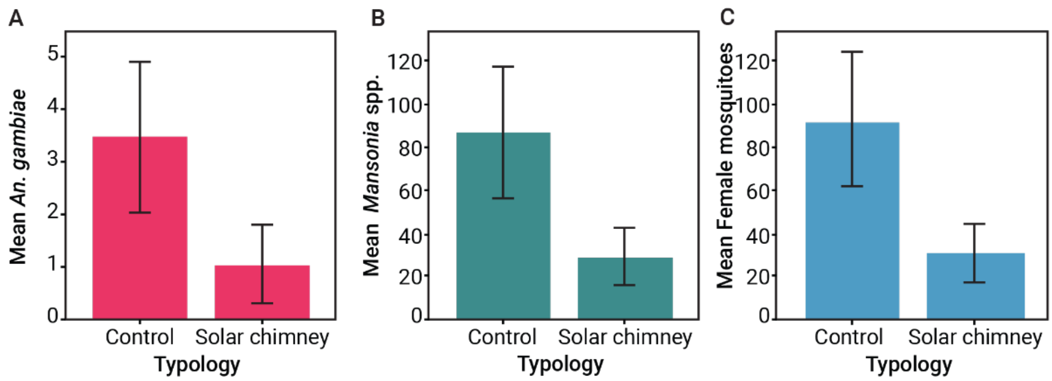

Figure 6. 8 Unadjusted mean mosquito number per night recorder for ceiling fans experiment. Where A = female *An. gambiae*, B = *Mansonia* spp. and C = all female anophelines and culicinae mosquitoes.

Adjusted analysis for cofounders (house number, sleeper pair, night number) showed a 91 % (95 % CI 90-92) reduction in *An. gambiae* and 71 % fewer (95 % CI 71-71) *Mansonia* spp. in houses with operating fans compared with houses where the fan was not operating (Table 6.4). Similar reductions were seen with female mosquitoes combined.

Table 6. 4 Female mosquitoes collected from houses with and without operating ceiling fans and adjusted analysis.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals.

Typology	Total	Mean/night (95% CIs)	Dif. from control house (95% CIs)	Protective efficacy (95% CIs)	p value
Female *Anopheles gambiae*					
Control (fan off)	101	3.5 (2.1 to 4.9)	Reference	..	..
Fan operating	37	1.1 (0.33 to 1.78)	0.09 (0.08 to 0.10)	91 % (90 to 92)	< 0.001
Female *Mansonia* spp.					
Control (fan off)	2491	85.9 (55.3 to 116.5)	Reference	..	..
Fan operating	978	27.9 (14.6 to 41.3)	0.29 (0.29 to 0.29)	71 % (71 to 71)	< 0.001
All mosquitoes					
Control (fan off)	2638	91.0 (59.6 to 122.4)	Reference	..	..
Fan operating	1032	29.5 (15.5 to 43.5)	0.28 (0.28 to 0.28)	72 % (72 to 72)	< 0.001

6.5.2 Environmental measurements

Average temperature inside both houses was 29.6 ºC during between 21.00 h and 23.30 h, 4.0 ºC higher than outdoor levels. During the second part of the night, 00.00 h to 07.00 h, mean temperature in both houses was 27.9 ºC, 3.5 ºC higher than outdoor levels (Figure 6.9). Further analysis adjusting for confounders showed no difference in temperature between the control house and the house with the solar chimney attached (Table 6.5). Relative humidity, however, showed a 31 % (95 % CI 20-41) reduction between 21.00 h and 23.30 h and a 32 % (95 % CI 26-37) reduction when comparing the house with working fan with a house where the fan was not working (Table 6.5).

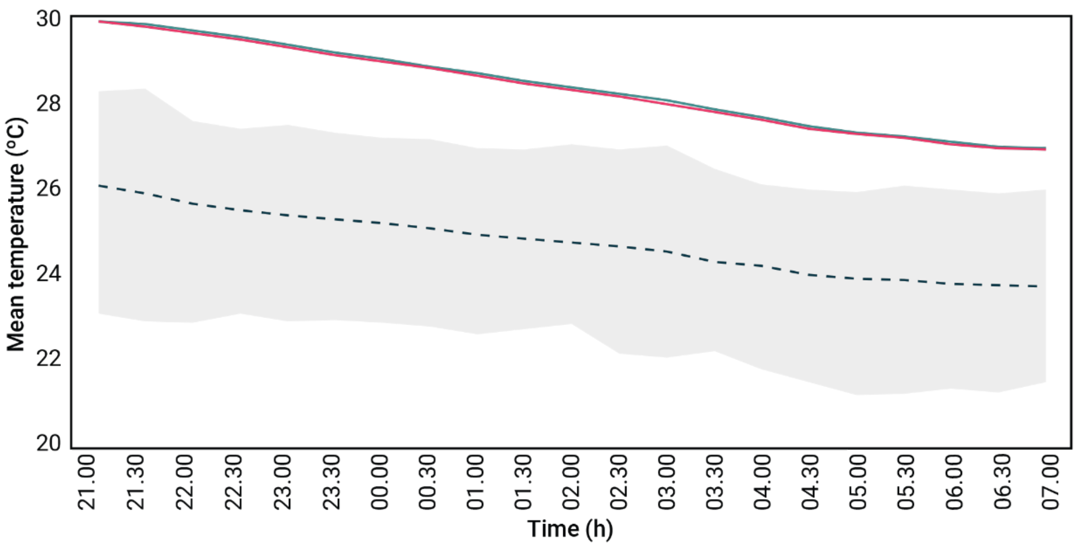

Figure 6. 9 Unadjusted mean indoor and outdoor temperatures recorded during experimental night of the ceiling fans experiment.
Gray area = minimum and maximum outdoor temperature levels, Green line = control hut, pink line = intervention hut and dotted line = outside measurements.

Table 6. 5 Average outdoor and indoor temperature, relative humidity and carbon dioxide concentration recorded during the ceiling fan experiment and adjusted analysis.
Generalized linear model adjusted for covariates (house position, sleeper pair and night). Figures in parentheses are 95% confidence intervals. Analysis shown only for the period the houses were occupied, between 21.00 h and 07.00 h.

	Average temperature from 21.00 h to 23.30 h			Average temperature from 00.00 h to 07.00 h		
	Average (ºC)	Difference from control house	p value	Average (ºC)	Difference from control house	p value
Outdoors	25.6 (25.5 to 25.8)	..	..	24.4 (24.3 to 24.5)	..	..
Control (fan off)	29.6 (29.5 to 29.8)	Reference	..	27.9 (27.8 to 28.0)	Reference	..
Fan operating	29.6 (29.4 to 29.7)	0.96 (0.81 to 1.13)	0.589	27.9 (27.8 to 28.0)	0.95 (0.82 to 1.12)	0.552
	Average relative humidity from 21.00 h to 23.30 h			**Average relative humidity from 00.00 h to 07.00 h**		
	Average (%)	**Difference from control house**	**p value**	**Average (%)**	**Difference from control house**	**p value**
Outdoors	98.8 (98.4 to 99.2)	..	..	99.3 (99.2 to 99.5)	..	..
Control (fan off)	78.5 (78.1 to 79.0)	Reference	..	79.7 (79.4 to 79.9)	Reference	..
Fan operating	78.3 (78.0 to 78.7)	0.69 (0.59 to 0.80)	< 0.001	79.5 (79.3 to 79.7)	0.68 (0.63 to 0.74)	< 0.001
	Average carbon dioxide from 21.00 h to 23.30 h			**Average carbon dioxide from 00.00 h to 07.00 h**		
	Average (ppm)	**Difference from control house**	**p value**	**Average (ppm)**	**Difference from control house**	**p value**
Outdoors	649 (633 to 665)	..	..	614 (607 to 622)	..	..
Control (fan off)	780 (765 to 795)	Reference	..	715 (705 to 525)	Reference	..
Fan operating	753 (742 to 763)	0.65 (0.40 to 1.08)	0.095	699 (692 to 707)	0.81 (0.73 to 0.89)	< 0.001

Evaporimeter measurements showed the water decreased by 0.26 ml/h (95 % CI 2.2-3.1) in the house with a working fan compared to 0.13 ml/h (95 % CI 0.9-1.8) in a house with a stationary fan. Analysis adjusting for confounders showed an increase of 319 % (95 % CI 319 to 319) evaporation in the house with the ceiling fan working compared with a house with the fan turned off (Table 6.3).

Indoor carbon dioxide levels during between 21.30 h and 23.59 h were higher compared to the ones between 00.00 h and 07.00 h. During the ceiling fan experiment, carbon dioxide levels peaked shortly after the sleepers entered the house around 22.00 h. Thereafter, carbon dioxide levels declined until 05:30 h, when there was a final increase. There was a lower carbon dioxide concentration indoors at night in houses with working fans (Figure 6.10). During the night, the house with the working fan had 94 ppm more carbon dioxide than outside levels, while the house with the fan turned off had 116 ppm more. Analysis adjusting for confounders showed that before midnight there was 35 % (95 % CI -8-60) less carbon dioxide in a house with a working fan than a house without a working fan, although this result was of borderline significance. During the second part of the night this effect reached statistical significance with a 19 % lower carbon dioxide concentration in the house with the fan on (95 % CI 11 to 27) compared to the house with the fan off (Table 6.5). Analysis of the whole night showed a reduction of 27 % (95 % CI 14 to 39, p = < 0.001) carbon dioxide levels in the house with the working fan compared with the house with the fan off.

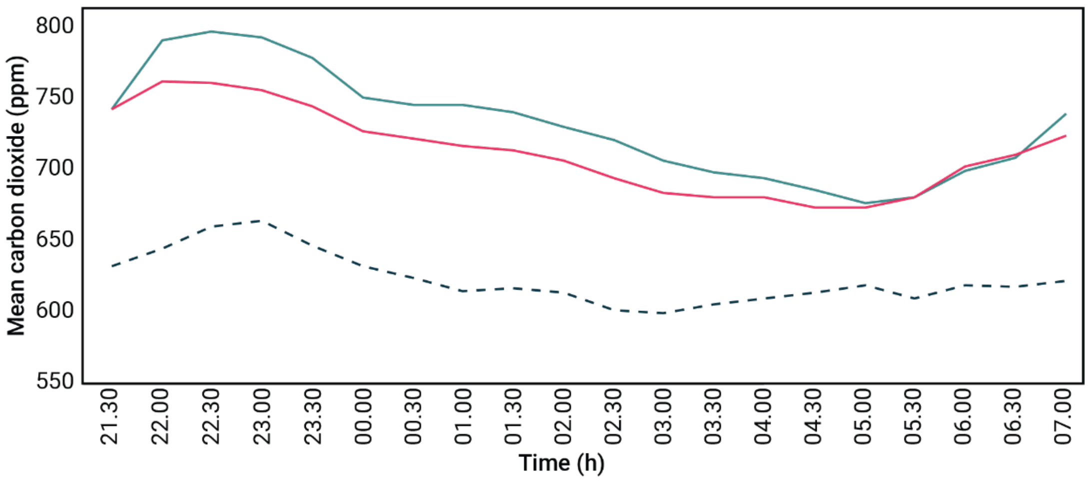

Figure 6. 10 Unadjusted mean indoor and outdoor night-time carbon dioxide levels recorded during the solar chimney experiment.
Where turquoise line = house with fan turned off, orange line = house with fan turned on and dotted line = outside measurements.

6.5. 3 Cost of intervention

The fan cost 22.1 USD and was attached to the metal structure of the roof.

6.6 Discussion

The findings of this chapter establish how passive and active ventilation affects indoor temperature, humidity, evaporation, carbon dioxide concentrations and indoor mosquito density. In this experiments evaporation increased by 61 % with the solar chimney installed and by 319 % with the ceiling fan working compared to the house without chimney and with the fan turned off during the night. The increased evaporation in ventilated houses can be translated into more a comfortable environment for the men sleeping inside the house. Evaporation is determined by temperature, relative humidity and air speed. Since there was little, if any difference in temperature and relative humidity between ventilated and unventilated houses, we are left with the conclusion that the increased ventilation indoors is due to increased air movement. Whilst the solar chimney was hotter than indoors during the day, it was cooler than indoors at night, making it impossible for the chimney to be drawing in air across the room at night. Instead, however, it may be that a ventilation current is produced in the reverse direction created by cross ventilation with cooler air being drawn down the chimney, into and across the room and then passed out of the screened windows on the far side of the room. Support for this hypothesis comes from the lower levels of carbon dioxide recorded in rooms with solar chimneys than those without, perhaps result from directly from increased ventilation and indirectly by reduced sweating of the men in the room caused by ventilation cooling.

The lower levels of carbon dioxide, a major mosquito attractant [37], inside a house with a solar chimney helps explain the lower numbers of *An. gambiae* entering these houses compared to those without solar chimneys. It does not, however, explain the increase in the number of *Mansonia* spp entering a house with a solar chimney compared to a house without a solar chimney. Clearly, further studies are required to explain this confusing picture.

In future, the design of the solar chimney could be improved by altering the orientation of a house, changing the surroundings around the house and the materials used for construction. Increasing the length of time direct sunlight fell on the solar chimney would have increased the temperature within the chimney, as would have preventing shadows from nearby trees falling on the solar chimney. The solar chimney was built with lightweight material of low thermal mass and a similar structure made from thick glass and higher thermal mass would have retained the heat better. Even though the outside wall was painted matt black to increase solar heating and an insulation layer indoors to prevent heat transfer from the external face into the room, the substantial heating of the indoor air caused by the metal roof nullified this effect. Painting the roof white [182], adding a ceiling or placing a green roof could increase the cooling effect of solar chimneys by reducing the temperature of the room during the day.

In the second experiment, using ceiling fans, there were large reductions in mosquito house entry in houses using a ceiling fan than those which were not. Although there was no difference in indoor nightly temperature in both types of house, the evaporation rate was considerably higher in a house with an active fan than one without. Since temperature and relative humidity were roughly comparable in both types of house, it is likely that the biggest increase in evaporation was due largely to increased wind speed caused by the rotating fan. This would increase the movement of carbon dioxide out of the screened windows and through the gaps around the two doors and, because it would have increased human comfort, would have reduced carbon dioxide production from individuals [122,183,184]. The combination of high indoor wind speeds and lower production of carbon dioxide would have both contributed to fewer mosquitoes entering the house. The average wind speed in the house was 0.5 m/sec. An experiment conducted in the field of mosquitoes approaching a host in The Gambia found that at air speeds higher than this value mosquito catches begin to drop off [49] In the laboratory, mosquitoes fly at a speed of 0.25 m/s when following an odour plume, [48] suggesting the higher wind speeds would restrict host location. The other important factor is that increased air speed indoors would facilitate the diffusion of carbon dioxide out of small openings in the house as well as cooling the men under the bed-nets, who in turn would produce less carbon dioxide further decreasing the attractiveness of the house to mosquitoes.

Using active and passive methods to increase ventilation and indoor comfort levels in the tropics have been studied previously [185–187]. It seems that there are, however, no experiments using solar chimneys to reduce mosquito numbers and keep the house cool at night. There have been several studies reporting the use of fans for reducing mosquito biting, although these were anecdotal, and for cooling indoors to increase bed-net use. In Kolkata, India, a study found that 53 % of respondents reported not using a bed-net and 80 % used fans instead to avoid mosquitoes [188]. In Ghana, a trial of a cooling fan placed inside a bed-net did not increase bed-net use [189].

There were several limitations to this study. Firstly, the studies reported here are pilot experiments carried out using only two experimental houses. Secondly, the experimental houses used in this study slept two adults in a single-roomed house, whilst the median density of people in such houses is four adults and children (M. Pinder, personal communication). Thirdly, many rural houses are line houses, where single rooms are split in two by a dividing wall, where the dynamics of heating and carbon dioxide may differ from our experimental set up. Fourthly, in most rural areas in sub-Saharan Africa, although this is changing in some parts[190], there is restricted access to electricity and, perhaps, a cultural resistance to the construction of solar chimneys as they differ from traditional housing prototypes.

The findings of this chapter show that active and passive cooling methods are effective at increasing indoor windspeed that reduces concentration of carbon dioxide indoors resulting in fewer mosquitoes entering these houses. Not only may it reduce mosquito ingress it may make it more likely that people will sleep under a bed-net at night further increasing protection from nuisance mosquitoes and those that transmit malaria. . Changes to indoor ventilation could have potential to reduce indoor malaria transmission and maintain the gains in countries that have achieved elimination.

Chapter 7 – Household activities of residents in rural Gambia during the rainy season and their implications for exposure to malaria and control: a qualitative analysis.

7.1 Abstract

7.1.1 Background

Malaria vector control activities are largely based inside and around the house. Understanding how different sections of society use and make decisions about their houses may help improve malaria control. This chapter records typical daily household routines and the attitudes of residents towards houses in two rural communities in The Gambia.

7.1.2 Methods

97 semi-structured interviews were conducted in two villages in rural Gambia towards the end of the rainy season between September and October 2021. Female and male participants were randomly selected and divided into categories based on their gender and their role in the house. Interviews were analysed using thematic analysis for the first round of coding and pattern coding during the second round.

7.1.3 Findings

A total of 53 female participants and 44 male participants were interviewed. What respondents consider a home consists of the house and the compound, a collection of houses shared by closely-related individuals delineated by a fence. Here, women are the primary active users of household space because they are in charge of cooking, childcare, fetching water, garden production, cleaning and other care-labour activities. Women often rely on each other for help with these tasks and other household chores. Elders are considered to be the advisors of the family and the village, and decision making is heavily influenced by them. Men spend most of their time outside the compound either fishing or engaged in agricultural production, depending on the village. Men generate the primary financial sources of income for the family, which is used for purchasing food, sending children to school, and construction work. Although men and family members abroad are primary providers, they rely on elders in the family for making decisions about how to administer money and other resources, and consult them before making decisions regarding the family and compound.

7.1.4 Interpretation

Since women spend more time in the compound than men, changes to the design of houses or house screening should involve them because such changes will directly affect their daily routines and house work. Elders should also be part of the

decision-making process when malaria interventions are directed at the home and compound. Since women rely on other women for help with household work and care of other members of the family, malaria treatment programs need to consider including all women that participate in care labour within the compound, including older women and teenage girls.

7.2 Introduction

Most malaria transmission occurs inside or close to the house at night [100]. For this reason, insecticide treated nets (ITNs) and indoor residual spraying (IRS), the major malaria vector control interventions in sub-Saharan Africa, are targeted at the home. Control may also be enhanced by combining these strategies with other house-based interventions like house screening and changes to the architecture of a house[41,58]. ITNs and IRS have contributed to the prevention of 87 % of malaria cases in sub-Saharan Africa between 2000 and 2015, by targeting the 79% of bites that occur indoors at night [34]. Such interventions will not, however, protect people from outdoor biting early in the evening or around sunrise when people are often outside their houses. Clearly, this indicates that additional protective strategies are needed to protect people from malaria.

One such approach is to reduce biting in the home by house screening or changing the architecture of the home, for example by raising the house off the ground [147,191] or improving ventilation to reduce the human scent used by mosquitoes to locate a host [37,69,122,127]. Little is known about how such changes to the built environment are received and interpreted by intended recipients, how the changes affect daily activities in and around the house and how they might reconfigure the daily activities of potential users. Understanding the daily routines inside and outside the house requires a deeper understanding of how local people view and use the house and the ways that this varies with gender, age and season. How a house is perceived by its occupants may provide important insights into the personal value of a building and how the structure is utilized.

In terms of understanding domestic routines in relationship to malaria transmission, a previous study in The Gambia [64] recording door opening and closing using loggers positioned on the doors showed a clear pattern of diel behaviour (Figure 7.1). People began moving in and out of the house from 06.00 h to 08.00 h, followed by a relatively constant period of activity between 09.00 h and 18.00 h.

Door opening and closing increased markedly between 19.00 h and 20.00 h, before dropping sharply from 21.00h to 06.00 h. In this study the authors speculated on what behaviours were being carried out at different times of the day. The current study is designed to identify which sections of village society are moving in and out of the house during the day and night and describe what they are doing.

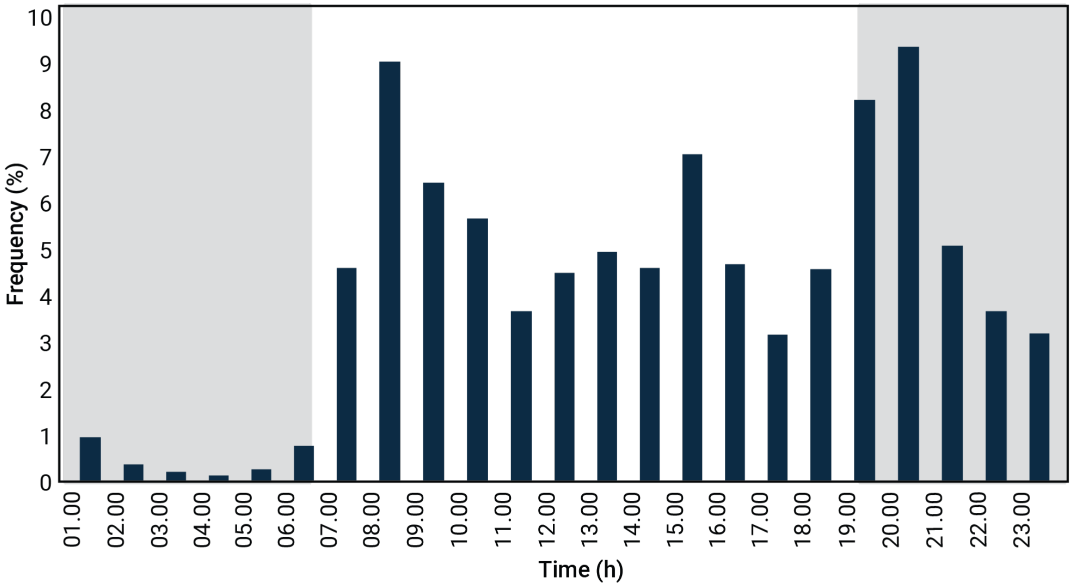

Figure 7. 1 Frequency of door openings in Wellingara village during the rainy season. Grey sections marking night time. Figure from Jawara, 2018 [64].

This chapter explores the daily practices and routines of women and men in two rural Gambian villages. The houses are single storey houses, typically lined houses consisting of a terrace of double rooms, one of which is a bedroom [64,101] (Figure 7.2). In The Gambia, houses mostly contain close relatives, and are clustered within a delineated fence, in an arrangement known as a compound. In the compound there may be a kitchen, a construction located separately from the lined-house that sometimes can be part of a pre-existent house, and a *banta ba*, a raised exterior platform made of sticks or concrete platform often used for sleeping during the afternoon and in the evening sometimes under a bed-net hanging from sticks located around the platform. Unusually for much of tropical Africa, the compounds in The Gambia are closely clustered together in a central nucleus, surrounded by a ring of agricultural fields. This arrangement is distinct from many other rural communities in the region where households are more dispersed. Therefore the concept of "compound" which includes not only the built structures but also the space surrounding them is more appropriate to describe the concept of 'home' [101,192]. The compound can be envisaged as composed of a series of layers that overlap one another beginning with the fence that separates the compound from the village, which contains the house (Figure 7.2), containing the bedroom, and finally the bed-net which creates a microenvironment for people resting. This chapter explores the dynamics occurring in the first two of these, the compound and the house.

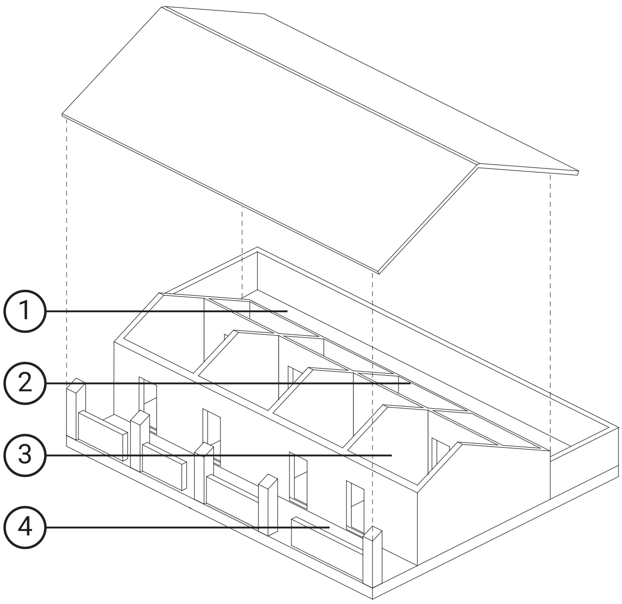

Figure 7. 2 Example of a rural Mandinka lined house.
1 = backyard, 2 = bedroom, 3 = first room/living room and 4 = parlour. Edited from Knudsen and von Seidlein, 2014 [101].

The description of routines that follows is focused on the rainy season, the period of intense malaria transmission [104]. Behaviour at other times of the year was not reported to avoid recall bias [193]. This study may help guide future malaria control activities focused on the home and surrounding area.

7.3 Methods

7.3.1. Study area

This study was conducted in Wali Kunda (N 13º34.25, W 14º55.28’), a fishing village, and Wellingara, (N 13º33.36’, W 14º55.46’) a larger village primarily engaged in irrigated rice cultivation in the Central River Division in The Gambia. These communities are 2.1 km apart and 4.6 km and 2.7 km from Brikamaba, the nearest small town. They are situated close to the largest area of irrigated rice fields in the country (Jahally Pacharr Rice Development Project). In 2013, the population of Wali Kunda was 114 and Wellingara 557 (Gambian census data 2013). Most people are of Mandinka ethnicity although there are a few Bambaras from Mali in Wali Kunda and a few Fulas from Guinea Bissau in Wellingara.

Each village has an *Alkalo* or village leader in charge of village activities. The position is inherited by lineage from fathers to the eldest sons, similarly to what happens within compounds with the first son taking over once he is old enough or in the absence of the father. These villages live patrilocally, where wives move in to their husband's family house after marriage [101].

The Gambia is located in the tropics and has a short rainy season between June and October, followed by a long dry season which is cold from November to March and hot in April and May [104]. Most malaria transmission occurs around the end of the rainy season, from August to November [105], with the highest number of cases and deaths occurring between September and November [106]. The vegetation is Sudanian savanna, with patches of secondary forest and bush interspersed with fields. The main crops in the area are rice, maize, cashew nuts, mangoes, cucumber, pepper, bitter tomato, okra and sorrel. In this area rice is grown in the dry and wet season because of the large irrigated fields introduced in the 1920s [194].

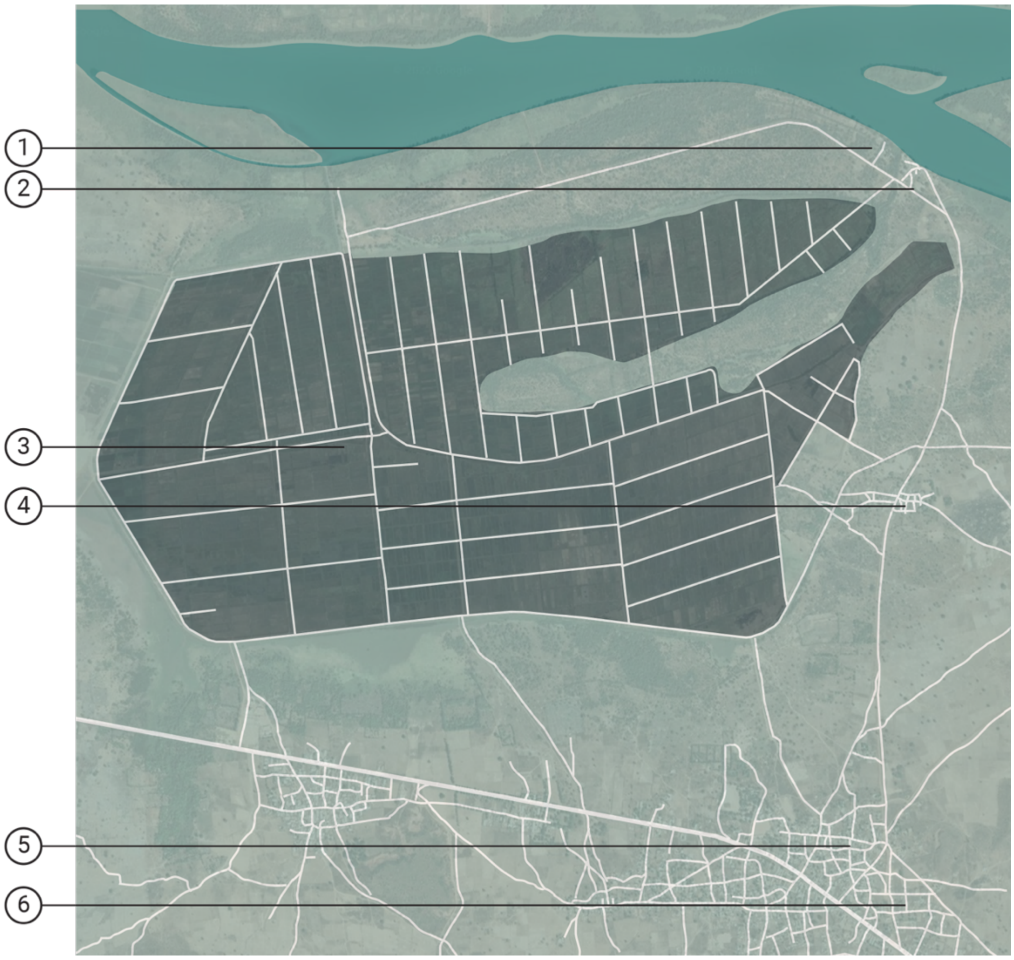

Figure 7. 3 Map of Wali Kunda, Wellingara and Brikamaba.
1 = Medical Research Council (MRC) Fieldwork station, 2 = Wali Kunda village, 3 = rice fields irrigated area, 4 = Wellingara village, 5 = Brikamaba town and 6 = Brikamaba Health Centre.

7.3.2 Human subjects

Prior to the start of data collection the research team met with the *Alkalos* of Wali Kunda and Wellingara for their approval to conduct interviews. Once they agreed, we proceeded to talk to the participants that were randomly selected. We obtained written informed consent from each participant before conducting the interviews. With illiterate participants we obtained their thumb print and we asked an impartial witness from the village to be present during the explanation of the research and to sign the consent form. All participants kept a copy of the consent form for future reference.

7.3.3 Data collection

All interviews were carried out with the assistance of a translator. At first, the interviewees were only women since they perform most of the household chores, but later other women and men of different ages in the compound were included.

Semi-structured interviews and participant observation [195,196] were carried out between September and October 2021. In each compound the wife or wives and a mix of the husband, young people older than 18 years, and elders, when present were interviewed.

The interviews started at the *Alkalos*' compounds and then continued by recruiting participants using purposeful typical-case sampling[197] since the purpose was to describe the average routines in these villages. All the compounds in Wali Kunda and randomly selected 63 % (22/35) of the compounds in Wellingara were visited. Most of the interviews were conducted in Mandinka and simultaneously translated to English by MCR fieldworkers who are fluent in both languages and trained in interviewing by MRC. A few interviews, mostly with men, were conducted totally or partially in English.

The semi-structured interview (Appendix 5) was concerned with understanding household routines. First, the interviewees were asked their name and village they were born in. This information was not recorded in the transcript but served to initiate the conversation. Second, all participants discussed what activities they perform each day and the times they did those activities. Thirdly, they were asked if there were days different from others, if their routine changed between seasons or by children going to school; here, only their answers regarding the rainy season are reported.

Interviews were audio recorded and the English dialogue verbatim transcribed [198] using online software (transcribe, Wreally LLC., Los Angeles, CA, USA). Transcripts were stored with the name of the village, a number per each compound (01 to 33) and number to differentiate the interviewee (1 to 5). Transcripts were grouped into six categories for analysis: women in charge of the compound (34), men in charge of the compound (29), elderly women (13), elderly men (3), young women (6) and young men (12). Data were analysed inductively, from specific observations to general themes [199] as Narrative Research. The daily routine of the participants is told as they lived it by re-storying [197] and rearranging the events chronologically. "Codable moments" [200] were marked during transcription and are presented as representative quotes of the thematic statements. Hard copies of the transcripts were analysed by themes and semantically [199] by writing reflexive thematic codes on the margins [201]. During the first coding phase instead of codes or short labels data were associated with themes or extended ideas in the form of a phrase or sentence [201]. After the first round of coding, themes were organized into a visual thematic map [202] (located in the results section) and reconfigured into thematic statements [203]. Analytic memos [201,204] written while transcribing and the first coding round were incorporated in the analysis for the thematic statements.

7.3.4 Environmental measurements

In order to better understand the impact temperature has on the routines in both villages indoor and outdoor temperature and relative humidity nightly measurements have been included in this chapter. Measurements were recorded every 30 minutes indoor with a data logger (TGU 4500, Tinytag, UK) located in the middle of the control rooms and outdoors with a weather station (MiniMet, Skye Instruments, Llandrindod Wells, UK) located 10 m apart from the houses. For Walikunda the recordings of a control house located within the MRC Wali Kunda field site and for Wellingara on the western edge of the village were used.

7.3.5 Ethics statement

This study was approved by The Gambia Government and Medical Research Council's joint ethics committee (15 July, 2021) and the Department of Biosciences ethics committee, Durham University, UK (22 July, 2021).

7.4 Findings

A total of 11 compounds were visited in Wali Kunda and 22 in Wellingara, and 97 interviews conducted. The characteristics of the respondents are shown in (Table 7.1). Following the routine description, I present the analysis from three thematic statements.

Table 7. 1 Characteristics of respondents

	Wali Kunda		Wellingara	
	Female	Male	Female	Male
Youths (18-21 yrs)	1	7	5	5
Household heads (22.60 yrs)	12	14	22	15
Elders (60-70 yrs)	4	1	9	2

7.4.1 Daily routine description

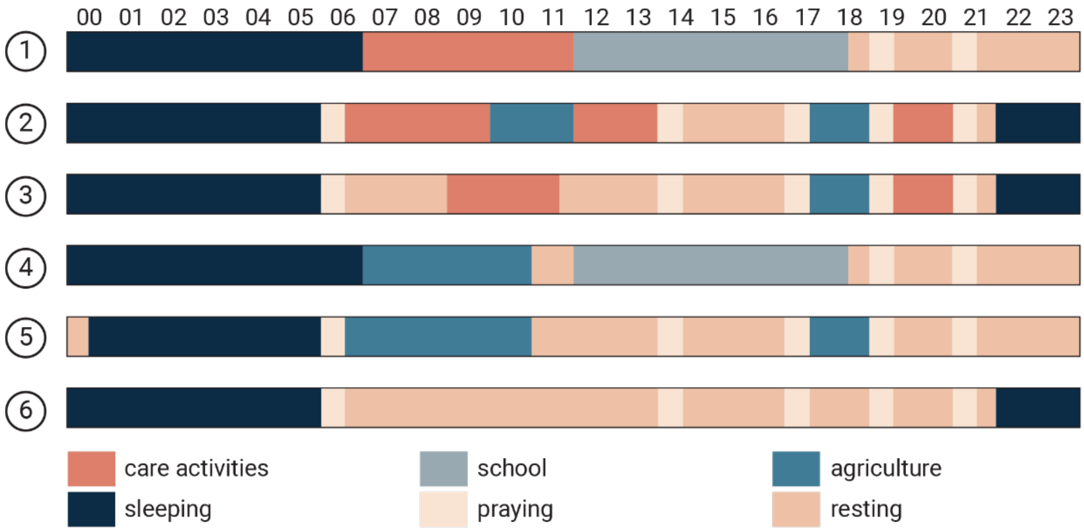

Figure 7. 4 Daily routines for different family members.
1 = women 18-21 yrs, 2 = women 22-60 yrs, 3 = women 60-70 yrs, 4 = 18-21 yrs, 5 = men 22-60 yrs and 6 = men 60-70 yrs.

Most participants reported waking up around the same time, at 06.00 h (Figure 7.4). The first activity of the day is similar for everyone: after performing their ablutions, men go to the mosque for *Fajr*, the first prayers, while women pray in their compounds. Although older women are permitted to pray at the women's room in the mosque, for the early morning prayer they stay in their compounds. After this, women will start their domestic work washing dishes from the previous night, sweeping the kitchen and the outdoor space of the compound and preparing breakfast inside the kitchen, which is usually located in a sheltered space or single-roomed building separated from the lined house. Some women reported warming left over rice from dinner the previous night so children going to school in the morning could eat before leaving the compound, around 07.00 h. In Wali Kunda, women fetch water between 06.00 h and 08.00 h when the water tap provided by the Medical Research Council (MRC) is open, and then again in the afternoon from 16.00 h to 18.00 h. Men working outside the compound leave for the farm or rice field around 07.00-08.00 h and depending on their activities for the day they return by mid-morning, lunch time or late evening.

Cooking breakfast takes 2 to 3 hours and occurs from 07.00 h to 10.00 h, depending on the quantity of firewood required and whether the wood is dry or not. After the rice harvest, between July and September, most family members eat breakfast in the compound. During rice cultivation, many family members leave the compound early to work in the fields before it becomes too hot and during this season they usually eat breakfast in the fields. Women in charge of cooking stay in the compound with children under five years old, considered too young to perform manual or agricultural labour or assist with water collection. The woman preparing breakfast takes the meal to the rice field, stays there working for some time before walking back to the compound to prepare lunch, awaiting for the return of the family around 14.00 h. In some compounds, women assign a child to take the breakfast to the rice field, while continuing with lunch preparation, laundering, sweeping the house and tidying up the bedrooms. In Wellingara, women reported fetching water around 11.00 h or 12.00 h, because they had to wait until the solar system could generate power for pumping water to fill the reserve overhead tanks after which water under pressure moves around water pipes in the village. Another common activity of women in Wellingara is that they sell cooking ingredients in the local market located on the main highway in the village between 08.00 h and 13.00 h. Here they sell surplus produce from their gardens and ingredients bought in large quantities in the nearby town and separate it into portions. Mothers-in-law stay longer to sell the produce and women in charge of the compounds leave to cook lunch as soon as they made sufficient money for school-lunch for their children.

The activities performed during the morning for families that do not own a rice farm or when the rice season has ended are usually divided by gender. Fishing is performed only by men at night or early in the morning depending on the tide of the river, while agriculture is a mixed responsibility depending on the crops cultivated and is performed only during daylight. Rice is the main staple food in The Gambia, and rice cultivation is the most important agricultural activity. Labour is divided between men, women and children. Men are responsible for ploughing the paddies and rice transplantation, whilst women sow seeds, weed the paddies, oversee protection of the crops from birds, thrash the grain from the plant, sun dry the grains, pack and transport the grain to a milling machine that removes the rice husks. Small children assist adults in protecting the crops from birds or are assigned to perform this activity on their own when they are not in school. Teenagers participate in transplanting, weeding the paddies and thrashing the grain from the plant. The rice grains are then bagged and sold by men. Vegetable gardens growing tomatoes, okra, onions, bitter tomato, pepper, cucumber and aubergine are worked by women and maize and cashew farms by men. A few men have non-agricultural related jobs, such as teaching, driving a taxi, tailoring in their own villages or in the closest town, something that was not the case for any woman interviewed.

By lunchtime, between 12.00 h and 14.00 h, teenagers attending school during the afternoon leave for school and children who attended in the morning shift will return to the compound. Lunch is usually served and eaten after the 14.00 h afternoon prayers, *Dhuhr*. After lunch, during the hottest hours of the day, there is an extended “relaxing time” for everyone in the compound which usually takes place at the *banta ba*. During this period, men and women perform similar activities like sitting, lying down, sleeping or brewing and drinking green tea. Additionally, women embroider curtains, fan the children, plait other women’s hair and prepare cooking ingredients to be used in the future, for example shelling corn or defoliating branches of baobab tree to be dried, pounded and added as a powder to food preparations, whilst some men read the *Quran*.

At 17.00 h, around *Asr* or late afternoon prayer time, women leave the compound and go to the garden, whilst men go to the mosque to pray. Both groups might return to their rice field at this time if there are activities to complete. Some women reported leaving their compounds with their children before 17.00 h so that they could pray at the rice field or vegetable garden. Agricultural activities continue until sunset, around 18.45 h. People then return to the compounds when it is time for *Maghrib,* early evening prayer at 19.00 h. Preparation of the evening meal or warming rice from lunch starts around 20.00 h, which is eaten after the last prayer of the day, *Isha*, at 21.00 h. After dinner, family members will stay outside the house but within the compound on the *banta ba*, where they lay down until the house is cool enough to sleep in. Some participants hang up bed-nets using wooden sticks placed around the *banta ba*, but these were primarily used by children and elders. Usually, women take children younger than 8 years old inside the house as they fall asleep, around 21.30 h, i.e. almost immediately after they have eaten dinner. Adults stay longer outside, but women mentioned they usually enter the house earlier than men due to tiredness. Men reported they walked around the compound to make sure everything was well before going inside the house at or after 00.00 h. The time spent outside depends largely on the temperature during the night with people staying outside until 00.00 h at the beginning of the rainy season when it is warmer and around 21.00 h by the end of the rainy season when the cold season is approaching.

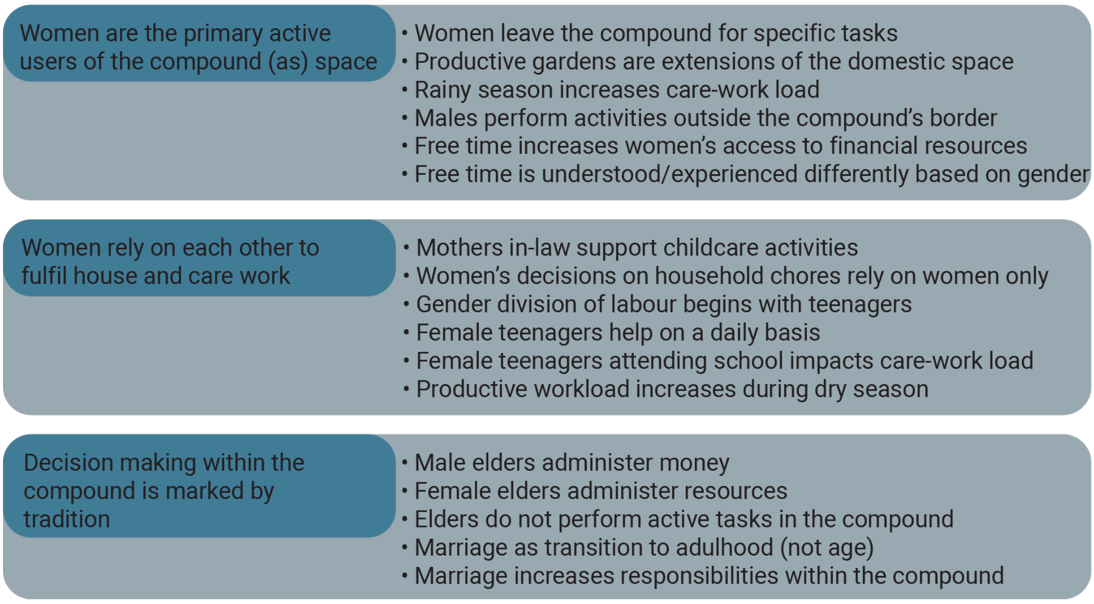

Figure 7. 5 Thematic map showing thematic statements and themes.

7.4.2 Thematic statement 1: Women are the primary users of the compound space

Most of the time women spent awake was in the compound performing some type of care activity. Within the compound they swept the house and compound in the morning and afternoon, prepared meals in the kitchen, kept the compound's water containers full, did the laundry, washed the children, ironed clothes and took care of children, elders and the sick. Nonetheless, some activities, like getting cooking ingredients, water collection or delivering meals at the rice field required them to leave the compound for short periods. Women also worked in small fenced gardens, sometimes accompanied by small children. The produce from gardens is mainly utilized for adding variety to the rice meal and any surplus is sold. Even when gardens are not located within the compound they are considered part of the compound and a space for women, as only women work them and have rights over their produce. As one interviewee explained, "we have one big [rice field] that belongs to the compound and we all go there, but we [the wives] also have our small, separate one"; whilst when talking about the garden "the compound [collectively] has nothing, we all [the wives] have our own garden". Women mentioned that their domestic work was more difficult during the rainy season, since freshly washed clothes took several days to dry and they had to put them in and out of the house. Cooking also took longer due to firewood being wet and general delay in their activities because of rain. When relaxing, women continued performing active tasks that would facilitate their care work (pre-preparing food ingredients), beautify their compounds (embroidering curtains), help other women (plaiting hair) or taking an active role in child caring (washing children, fanning and rocking children). Women distributed their time between fulfilling their household activities and the ones performed in their resting time. A woman said that when she is asked to plait other women's hair she will tell them "to wait until I have prepared my lunch, when I have prepared my lunch I plait those who have asked".

Men's activities are usually performed outside the compound. In the compound men are in charge of house building and repairs. Some men remove weeds or grass and clean the area next to the outer side of the compound wall. While in the compound the activities that take most of their time is relaxing, accompanied with brewing green tea, chatting with friends, reading the *Quran*, praying and occasionally watching over the children.

7.4.3 Thematic statement 2: Women rely on each other to fulfil housework and care labour.

Women reported having help from other women in the compound for care and household activities. Most female participants had one co-wife and a few had two co-wives. If there are two co-wives in a compound, an individual woman will cook for two days and then have two days off cooking, whilst where there are three co-wives, there will be two days of cooking followed by four days of no cooking. When it is their turn, women clean the common areas of the compound, fetch water for cooking and cook for everyone in the compound. The days they are not cooking for the compound, women do laundry for their nuclear family and in-laws if she is the first wife, spend more time in their gardens or have a "relaxing" day. When a wife is pregnant, she can be released from her care activities by the other wives.

Women also reported having help from their mother-in-law, especially in activities related to childcare. Mothers-in-law not only oversee childcare but are also active in washing, feeding, cleaning, rocking and buying things for children. Women usually leave their children with their mother-in-law while going to work to the garden or rice field. Grandmothers also mentioned that they took the children for the monthly check-ups at the closest health centre in Brikamaba. Women and mothers-in-law mentioned they keep the doors of the house open, enabling children to go inside the house and take food items or water without the assistance of any adult. Women also relied on children, especially teenage daughters, for household chores.

Teenagers would help with activities ranging from helping with food preparation to preparing one meal a day, doing laundry and taking care of their younger siblings. Age is a determinant for daughters' help in the household, a women having three daughters under 8 years old said "[them going to school] doesn't [change my routine], they are not powerful enough to help me". One young woman mentioned helping her sister in-law with cooking lunch and washing her mother's clothes. The help from family in-law, however, is not compulsory and women cannot rely on it.

Women reported that when their teenage daughters were at school they felt an increase in house work. A mother of two teenage women said "if they don't go to school they will help me in all these things [household tasks]. I can assign one to cook and the other to fetch water and I will sweep. If they go to school, I don't have a choice I have to [do it alone]". The same was not the case with teenage sons as their tasks, such as collecting firewood, did not have to be done daily. One woman mentioned that before the interview her son was helping her with laundry until one of the elder women in her family told her that, "washing [clothes] is not good for men".

7.4.4 Thematic statement 3: Decision making within the compound is shaped by tradition.

Once the first son of the first wife is old enough, in his mid-twenties, he takes over the financial responsibility of the compound. He is also expected to marry and for his wife to take over the domestic activities of the compound. Once a woman is married, she moves to her husband's compound, and takes full responsibility of care activities, or if there are other wives, partial responsibility of care activities. As an elder woman puts it: "In our Mandinka tradition if your son has a wife as a mother your responsibilities decrease. When your son has another wife or his brothers have a wife they can share responsibilities among them. In our tradition if your son has a wife you are kind of free". Arrangements between wives are their own and men are not involved in them. In the absence of a mother-in-law, the first wife organizes the other wives' activities in the compound. While the evident activities are transferred to the first son and his wife, the responsibility over the compound's wellbeing and decision-making stays with the elders. Male members of the family give their earnings to the eldest man in the compound for its administration, while the elder women are in charge of distributing rice and other cooking ingredients. In regards to these practices, a woman told us that it "is tradition, traditionally it is what we do. The elders in the compound are responsible for measuring the rice and giving it [to the woman doing the cooking], we do it because of our experience". Multiple single-male interviewees from Wali Kunda reported giving their mothers the fish they caught for her to sell. Elders also reported that children asked them for lunch money, as they knew they were administering the compound's money.

Single women, as mentioned earlier, were not responsible for household jobs and their intervention in those activities was voluntarily unless assigned by their mothers. Single men and women had more freedom than the married ones who carried responsibility for the compound. While single men contributed to the compound's economy and handed over their earnings to one of their parents, they had freedom to move and fewer responsibilities in the compound.

7.4.5 Environmental measurements

Heat was mentioned as an important factor in determining how houses were used, particularly influencing the time to go inside the house to rest which was late at night because heat made dwelling spaces uncomfortable. Environmental measurements were recorded for entomological experiments conducted parallel to this study and are presented here as reference (Figure 7.6). Temperature in both villages followed a similar pattern with temperatures starting at around 26 º C between 06.00 h and 10.00 h and reaching its maximum value in the period between 14.00 h and 17.00 h from where it began to decrease. Temperature in Wali Kunda was higher than in Wellingara from 06.00 h to around 19.00 h. From midnight, temperature in both villages decreased to 25 ºC, the coolest temperature point in the day.

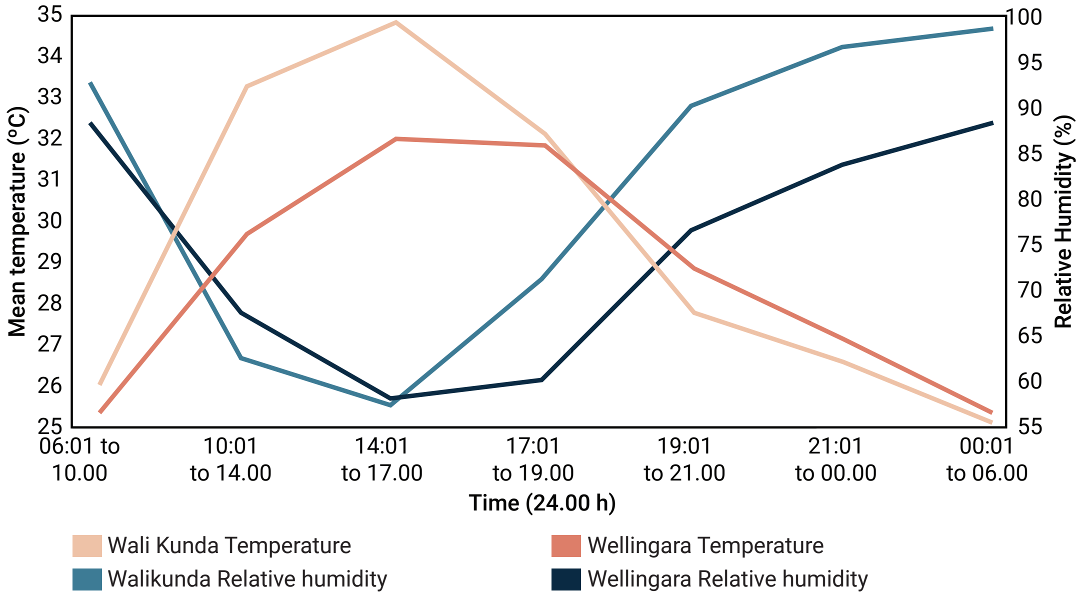

Figure 7. 6 Outdoor mean temperature and humidity in Wali Kunda and Wellingara at different times of the day.
Measurements recorded during September 2021.

7.5 Discussion

This chapter explored and analysed the activities of adults and young people of different genders in the home and compound. Daily routines differ by gender, age, role within the compound and season. These differences might shape exposure to mosquito and mosquito biting. During the rainy season, the period of malaria transmission, domestic activities during the day are split clearly between genders. Women are in charge of the compound's care-labour, the well-being of family members and the produce of their gardens. Women of different ages stay in the compound most of the day while performing domestic tasks. Through their various activities, the way they perform them, and the interaction between care labour and household chores , women give the physical space of the compound it's meaning of home. While the physical space, the house, construction is paid for and/or done by men with assistance of women in fetching water, transporting mud and blocks and feeding, the home as the space where the family lives and develops gets its meaning assigned because of the routine activities of its users [95]. These activities are likely to differentiate malaria transmission by gender and age. Morning activities might place women in a higher risk of getting mosquito bites compared to other members of the family whose primary activities are performed outside the compound. Because human scent might be more concentrated around the house that in the mosque, women praying at their compounds might have more probability of getting bitten than men. Women in charge of their households and young and old women assisting them might be exposed to mosquitoes resting inside and around the house while sweeping the compound and the rooms, fetching water or cooking. Similarly elder women and men who use the compound as a relaxing space are among the primary users of the compound, but their role is more passive than other actors in the compound which might increase their risk of getting mosquito bites.

As reported by the participants, men mostly rest, eat, relax and sleep in the compound. They might be more likely to encounter resting mosquitoes when they clean the grasses and weed the outside façade of the compound wall. At night all members of the family might be equally exposed to malaria infection when mosquitoes are active [100] and people rest outside or get up at night. People stay outdoors longer at night when their houses are too hot, exposing themselves to mosquito bites, or simply do not use an ITN because it creates a microclimate that is too uncomfortable[3].Women and children might be an exception because they are more likely to be under a bed-net, following current health guidelines. In the evening young children were the first to be put to bed indoors around 21.00 h after dinner and as soon as they lied down and fell asleep on the *banta ba*. A previous large study showed that in other parts of rural Gambia, most under five years old were put to bed shortly before 22.00 h [165]. Women usually followed the children indoors because they were tired and wanted to rest. Men were typically the last ones going to bed after securing the compound, with the exception of young men, who attended parties sporadically staying up later in the night at peer group social gathering or partying. In these Muslim villages people also wake up and leave their beds early in the morning for prayers when mosquitoes are still biting. Consequently, one would expect that malaria would be more prevalent in men, particularly younger men, and these groups would be more likely to have malaria than women and children since they spend less time under an ITN and ITNs distribution programs are mainly targeted at women and children under five years for whom malaria is more severe [205].

In a previous study in Wellingara, data loggers were used to quantify when doors were opened and closed during the day and night (Figure 7.1) [64]. The increase or decrease in door opening can be associated to activities reported by the participants. Door opening increased markedly from 06.00 h to 08.00 h corresponding to when people woke up and prepared for the day; dressing, performing ablution, praying, children getting ready for school and women cooking breakfast and cleaning. From 09.00 until 18.00 h activity was less intense since many adults were working outside the compound or the house. From 18.00 h until 20.00 h activity increased markedly, corresponding to the preparation and eating the evening meal, showering and prayer. Door opening declined progressively from 20.00 h, as different members of the family retired to bed, with young children, women, men and young men going to bed in that order. From 00.00 to 06.00 h there was little activity at night with people occasionally making nocturnal visits to the toilet. A previous study in rural Gambia showed that pregnant women urinated twice as frequently at night compared to their non-pregnant sisters, increasing the chances of malaria infection during pregnancy [206].

In sub-Saharan Africa, malaria vector control interventions like the use of ITNs and insecticide residual spraying (IRS) are designed to protect people staying indoors and to reduce mosquito numbers, they however are not protective against outdoor biting mosquitoes in the early evening or if people get up early and leave the protection of their houses. Modifying some practices that might be exposing people to malaria including sleeping outside, not using a bed-net while sleeping or praying under a bed-net, might be possible by modifying the house's infrastructure. The main reason reported for not going early inside the house and not using a bed-net at night is that the house is too hot [3]. In the present study people reported the time they spent indoors or outdoors at night depended on how hot or cold the house was at the time. The differential use of houses depending on the temperature was corroborated by reports from participants in this study, who said that they delayed their entry to the house when it was too hot. During the hottest time of the year they reported sometimes spending the entire night outside because the house was too hot. Cooling a house is possible using a variety of techniques like screening doors and windows [69] or providing cooling devices like fans [172]. A previous study conducted in The Gambia [207] found that the propensity to sleep outdoors was greatest in the hot dry season when 42 % of participants slept outdoors compared to the cooler, but still hot, rainy season where 2-3% slept outdoors. Although it was not possible to disentangle whether this behavioural difference is due to high temperature alone or the combination of high temperature and mosquito biting seen during the rains. The same study, determined that a substantial amount of biting took place between 04.00 h and 06.00 h. This biting time might specially affect people preparing to pray in the early morning. For *Fajr*, dawn prayer that comes with sunrise, people perform ablutions before prayer at the mosque or in their houses. Both activities performed outside the bet net mark the beginning of the day. Here, activities like praying, where people stay still with intermittent movements might increase the likelihood of be bitten by mosquitoes compared to more active behaviour like walking home from the rice fields. Modifying infrastructure to prevent people getting bitten while praying is more complex as this activity requires the person to be standing and moving. An alternative could be to provide a fixed screened cover to replace the sticks placed around the *banta ba* where bed-nets are hung at night. Getting bites while praying, however, was not mentioned as an issue by the participants.

Entomological studies in this area have demonstrated that ventilating houses with mosquito screening or raising a house off the ground can dramatically reduce the number of malaria mosquitoes entering a building. A study looking at acceptably of screened doors and windows [208] found that most of the self-closing front doors where propped open during the day and that users had added a curtain behind them. Traditionally, doors are usually left open to increase air flow and for small children to be able to go inside and out without somebody opening or closing the door for them. This is one of the strategies women use to reduce their care labour load. By leaving the door open and having the curtain as a visual separator of the public and private space, they protect their houses from outsiders but also allow members of the family, like children, to go inside the house easily. When considering building elevated houses it is necessary to think how this might affect people using the house. In this context houses are designed on the same level and people are not used to stairs, women carrying sleeping children would have to take the stairs to an elevated house, so it would be important to have well-constructed stairs with handrails. Another consideration that needs to be addressed is the kitchen, even when it is located separately from the bedrooms since the difference in levels might increase the time and difficulty in performing household chores. A housing project in Tanzania aiming for malaria prevention addressed this issue by building the kitchen and store on the ground level and the sleeping spaces on the first floor [209]. An interdisciplinary study in malaria in urban Ethiopia identified how housing design that does not take human behaviour into consideration might place people at risk of contracting vector borne diseases [210]. In this study, owners of apartments with windows that could not be opened, broke the glass from windows and covered them with pieces of carboard or using other makeshift strategies. This ventilation problem could have been solved by having screened windows from the design stage or by providing people with windows that could open and close to increase ventilation in their houses. Another problem identified by the study was that the design of the kitchen did not respond to local cooking traditions and people ended up installing their kitchens in the corridors. Even though smoke, like the one produced by cooking with charcoal in this study, has been related to reduction of mosquito numbers [211] the human scent remaining in the corridors after cooking times might lead mosquitoes inside houses. Although the urban context largely differs on the rural one, it is important to acknowledge the role that holistic design and users behaviour have in health outcomes.

Vector control strategies cannot be successful on their own. They require the engagement of the people who will use them, and appropriate use to provide the desired effect. The findings of this study suggest that there are key moments and stages to involve specific village stakeholders. Women; for example; are in charge of managing the household and are the main active users of the compound. They primarily rely on their co-wives to assist in their work for the whole compound. It is a similar situation for young women, although for shorter periods than the older women, who must assist with household chores when they are not in school. Children aged 10 years to 13 years and teenage girls will take over feeding and care responsibilities of their mothers. As they grow up the activities they perform last longer and become more complex. Young girls assist with fetching water, watching over younger siblings, while teenage girls might cook whole meals by themselves. Women are also supported by their mothers-in-law when washing small children, taking children to the toilet, preparing seasoning ingredients, peeling vegetables for food preparation, all activities that contribute to accomplish main care labour tasks or that allow women to be more efficient in their chores. Elder women also perform their own activities, including commercial ones, but for most of the time they are resting in the compound. Because women at different stages of life are the main users of the compound it is more likely that vector control strategies placed in the household will impact their routine and increase or decrease their workload. It makes sense to include women in the design process as they can provide insights on how the strategies will be used in real contexts and how to improve them.

Similarly to many other agricultural societies, in this setting women are in charge of the care-labour in the compound, responsible for care of the sick at home and taking children to the health centre for check-ups or when they are sick [212]. In some cases, women pay from their savings for treatment and for medicines at the hospital and drugstores. Sometimes this amount is reimbursed by husbands who were not present at the time or who live in other city or abroad [213]. When they walk to and from the health centre, their household activities are frequently taken up by other women of the family, usually the mother in-law or one of the daughters. Some women also mentioned belonging to a *kafo*, a group traditionally formed by cohorts of women of the same age who were circumcised at the same time and place during a religious ceremony, which in these villages included the all women in the village or women grouped by their occupation. The activities associated with the *kafo* were not performed on a daily basis but were reported by women as a source of help among them. The women organized in large groups worked in agriculture, saving money as a group or dividing it individually as wages after large rice-cultivation systems were implemented in The Gambia [194]. Some elder women had their own businesses, usually selling cooking ingredients in their compounds or, in Wellingara, a stall in the highway market. These income generating activities are possible because of the time that they possess once their daughter-in-law is in charge of the compound's care. Participants reported that these groups of women organized weekly or monthly money collections and then raffled it among its members. When they received the money from the monthly or weekly raffle they mentioned saving it for school lunch, buying clothes for themselves and their children and for paying for medical treatment. There are *kafos* formed for celebrations only, they contribute with money, work and household or food items following one of the original purposes of these groups [194]. This suggests that women often use their own savings and resources to manage the costs of health care and may be more likely to invest in malaria prevention or treatment activities. Related to practices to prevent malaria transmission, a study found that households headed by males were more likely to use them than households headed by females [214]. This might be an effect of female-headed households experiencing higher levels of poverty and less access to information. This reinforces that malaria prevention strategies should be multisectoral as family finances, education and development have a big incidence in the adoption of malaria prevention strategies.

Elder women have responsibility for distributing the ration of rice in the compound, this is crucial because it is the staple food for the family and needs to be protected. Whilst it is usually men handing this responsibility to women, they do it because they have confidence in their good judgment and knowledge related to care labour. The fact that they have income of their own and that their advice is valued in the family makes them important actors in decision-making. Older men also experience an increase of their free time when their sons take over the financial burden of the compound. They, however, use this time to increase their religious knowledge and to rest. Men in the compound performing income generation activities hand their income to the eldest man in the compound for administration. Family members working abroad will send money to elders in the family or men in charge of the compound who will transfer it to the elders. When taking decisions related to the compound, elders are frequently consulted on their opinion and their advice has considerable importance. This might be due to the tradition of respecting elders and is reflected in the decision making of the family. A study in rural households in Ghana the role of elders extended to approval or not of seeking medical treatment at the hospital or with the local healer when a child was sick [213]. Women were not the official decision makers in the study but they found ways of contesting the power structure by taking sick children to the hospital and paying with their savings. This part of the analysis suggest that at the moment of presenting vector control strategies to the families and villages the approval from elders is crucial as their engagement will influence the attitude of the rest of family members.

Men are responsible for the compound's economy, children's school fees and for providing food, and perform most of their active roles outside the compound, using the compound largely as a resting and relaxing space. Remittances from men living overseas also contribute in supporting the household. This is also the case for young men, who carry out agricultural activities such as working in the farms or rice fields, animal husbandry and household chores such as fetching firewood for cooking. Similar to elders, men's engagement is important at the moment of presenting and implementing projects. Since they are the ones in charge of the financial they are the ones that can assign the compound's financial resources and invest in vector control strategies taking place within and in the space surrounding the compound.

This study has several limitations. First, both study villages are representative of uncommon and specialised types of village: Wali Kunda is a fishing village and Wellingara is situated close to the only area of large-scale irrigated rice cultivation in the country. Secondly, respondents were mostly Mandinka. Although this is the major ethnic group in the country, differences are likely with other ethnic groups in rural Gambia. Thirdly, asking about daily habits in people is challenging because they are often performed automatically without thinking, therefore some relevant activities may have gone unreported in the interviews. Fourthly, no questions were asked about the activities of children from zero to four years old who are most at risk of malaria [205]. Fifthly, the study was conducted by outsiders to the villages. This might have prevented us from gaining deeper understanding of certain practices but also allowed us to explore topics that have been normalized by community members so much that they perform them automatically.

Since women are the primary active users of the compound any change in its infrastructure is likely to affect their routine and might place an extra burden on them or contribute to the make their activities easier. Therefore, it is important that design of home-based vector control strategies is done along with their input. Elders hold power within the family, they are advisors for women and men in charge of care and finances of the compound. It is important that they are also involved in the introduction of control strategies. For control to be successful they will need to understand the benefit of any intervention, so they give their blessing and the whole compound supports it. With women of different ages participating in health-related activities, like taking care of sick people at home or taking them to the hospital raises a question of how medical seeking behaviour and healthcare activities could be performed by addressing women as a group and not only pregnant women or mothers of children under five years who are part of vulnerable groups. With the need for widely accepted vector control strategies that complement existing methods, it is important to explore how changes to the built environment would be impacted by human behaviour.

Chapter 8. Discussion

8.1 Summary of chapters

The overall goal of this thesis was to explore elements of the house that could be altered to produce successful strategies to reduce the transmission of malaria and increase the uptake of existing vector control strategies targeted at homes.

Chapter 1 reviews the effect of malaria on health, economic output and development, the history of malaria control efforts and the challenges its control presents. It is also an introduction to the relationship between the built environment and public health since the early 1900s, focusing on the links between malaria and the household in sub-Saharan Africa.

Chapter 2 describes an experiment conducted to find out if elevating a house would reduce indoor mosquito density and make the house cooler. The study took place in Wellingara village, The Gambia, during the rainy season 2019 with four experimental huts, each of which could be moved up and down. The huts were wooden with a corrugated metal roof. They had two corrugated doors, at the front and the back, similar to the doors in the surrounding villages. It was hypothesised that raising a house from the ground would reduce indoor mosquito density and make the hut cooler at night. The huts were kept at heights of 0 m, 1 m, 2 m or 3 m every four experimental nights. Every night two men slept in each hut, and the pairs rotated between huts every night for the duration of the experiment. Mosquitoes were collected using light traps nightly from 21.00 h to 07.00 h and environmental measurements recorded. Elevating a hut from the ground reduced female *Anopheles gambiae* hut entry by 41 % at 1 m, 68 % at 2 m and by 84% at 3 m, compared to the hut on the ground. The only difference in temperature between the huts was presented between 00.00 h and 07.00 h when the house at 3 m was 18 % cooler than the control hut. These findings suggest that elevating a house from the ground is an effective measurement to reduce mosquito house entry and to prevent malaria infection.

Chapter 3 reports an experiment that was designed to find out if more mosquitoes entered huts elevated 2 m above the ground if the space under the hut was closed. The study took place in Wellingara village, The Gambia, during the rainy season 2021 with four experimental huts, each of which could be moved up and down. For the experiment three huts were elevated at 2 m and one kept on the ground as a control. The elevated huts had the space under the hut with: a) no walls, b) closed with air-permeable walls (screening) or c) solid walls (plywood). Mosquitoes were collected and environmental measures recorded every night in the same fashion as described in chapter 2. Pairs of men were rotated between huts each night. Hut treatments changed every four experimental nights, where one house was elevated at 2 m and one taken down to the ground and different types of walls changed between the three elevated huts. An elevated hut with no walls underneath had 53 % less mosquitoes, the raised hut with air-permeable walls underneath 24 % less mosquitoes, and the raised hut with solid walls underneath 31 % less mosquitoes compared with the hut on the ground. Indoor temperature and carbon dioxide concentrations were similar in all huts. The results of the study suggest that the indoor mosquito reduction effect achieved by raising a house from the ground is reduced if the space underneath the house is closed.

Chapter 4 presents the results of data collected to determine the effect of house roof colour in indoor temperature and its implication for malaria control. Data was collected in 2018 from two inhabited single-room experimental houses built within the Medical Research Council's (MRC) Wali Kunda field site. Houses had mud-brick walls, corrugated metal roof, three badly-fitting doors and no windows, replicating similar conditions in local villages. Roof types were a) original bare-metal, b) painted with oxide primer or c) white gloss. Results showed maximum daily temperatures were 0.93 ºC lower in a house with a white roof compared with a house with bare metal. At night, between 21.00 h and 23.59 h houses with white roof were 1.74 ºC cooler and houses with red roof were 1.23 ºC cooler than the house with bare metal roofs. Similar results were found for the second part of the night, from 00.00 h to 06.00 h. Houses with white roofs were comfortable 87 % of the time compared with houses with bare-metal roof that were comfortable only 13 % of the time. People in a thermally comfortable house may be more likely to use malaria protective measures like insecticide treated nets (ITNs). Painting the roof white is a cheap an easy way to make a house more comfortable and, potentially, increase net use at night.

Chapter 5 describes two experiments assessing the importance of screening to reduce indoor mosquito density and temperature, whilst increasing human comfort. The study was conducted in two identical experimental single-room mud-brick houses in Wali Kunda MRC field site in the rainy season 2019. In the first experiment the intervention house had two 0.65 m^2 screened windows on opposite walls of the house and the control house no windows. Results showed that the house with screened windows had 38 % less female *An. gambiae* mosquitoes and were 17 % cooler between 21.00 h and 07.00 h compared to the control house without windows. The second experiment compared a house with screened doors at the front and back of the house with a control house with only two badly-fitting solid doors, similar to those in surrounding villages. Houses with screened doors had 76 % less female *An. gambiae* and were 42 % cooler between 21.00 h and 23.30 h and 44 % cooler between 00.00 h to 07.00 h compared to the control house. Night-time comfort levels in both intervention houses, screened windows and screened doors, were higher compared to control houses with no screened or less screened area of façade surface. Screened surfaces reduce mosquito house entry, probably by diffusing host odours such as carbon dioxide and reducing its concentration in the room due to better ventilation and temperature reduction.

Chapter 6 presents two experiments which measured the effect of passive and active ventilation on indoor mosquito entry and human comfort and in two experimental houses in Wali Kunda field station. The first experiment explored the cooling effect of a solar chimney, a passive cooling device, attached to one side of the house. The solar chimney consisted of a right triangular prism supporting translucent sheeting on the hypotenuse and abutting one wall of the house wall floor on the other sides of the prism. The hypothesis was that air will heat up inside the chimney, go up and leave through the opening on top of the translucent sheeting, drawing cooler air from the room into the chimney. Although there was a 26 % fewer female *An. gambiae* in the house with the solar chimney, the indoor temperature at night was similar in the intervention and control house (21.00 h to 07.00 h). The second experiment looked at the effect of operating ceiling fans indoors, an active ventilation strategy, on indoor temperature and mosquito house density compared with a house with no fans. There were 91 % fewer female *An. gambiae* in the house with working ceiling fans compared to the control house with the fan turned off. Temperatures were similar in both houses between 21.00 h and 07.00 h. The results suggest that the heating effect on the solar wall was insufficient to maintain the air interchange at night and therefore the odour attractants emanating from the house were not reduced in the test house. During the second experiment, although there was no temperature difference between the control and intervention house, the ceiling fan reduced the number of mosquitoes attracted to the trap, probably due to the strong winds produced by the fan. Passive ventilation techniques should be explored further as ways of making a house more comfortable and as an alternative to electricity-based ones. Active ventilation proved effective in increasing human comfort which might make people more willing to use bed-nets at night.

Chapter 7 investigated the daily routines of people living in Wali Kunda and Wellingara villages in The Gambia, between September and October 2021. Responses of different groups of women and men about their daily routines in and around the compound during the rainy season was recorded during interviews. The analysis focused on how the activities and actors relate to malaria vector-control strategies. A total of 97 interviews were conducted in 11 compounds in Wali Kunda and 22 in Wellingara. Interviews were simultaneously translated from Mandinka to English, audio recorded and transcribed. For the analysis, participants were divided into six groups: women in charge of the compound (34), men in charge of the compound (29), elderly women (13), elderly men (3), young women (6) and young men (12). Transcribed data were analysed thematically and findings presented as thematic statements. Since women were the main users of the compound, vector-control activities operating in this space would most likely affect their routines, in a positive or negative way. That is why it is important to include village women in the design of vector-control strategies. Female and male elders in the compound play an important role in the compound's decision making. They are the guardians of financial and in-kind resources and provide advice to the other members of the compound. It is important that they understand the benefit of and approve vector-control projects to increase the chances of other members of the family adhering to the project or study. Finally, the chapter discusses how women rely on other women, mothers-in-law, sisters-in-law or daughters, to fulfil their household work and care labour. Even though this might not have direct implications in vector control programs it is an important point to consider when designing programmes for malaria treatment and strategies to improve medical-seeking behaviour.

8.2 Study limitations

Specific limitations have been discussed in the individual chapters of the thesis, there are, however, several limitations that affect all chapters. First, entomological experiments, described in chapters 2, 3, 4, 5 and 6, were pilot studies, limited to small samples of experimental huts or houses. Future studies would need to assess the impact of house modifications on larger numbers of village houses and in different parts of sub-Saharan Africa to determine whether the findings could be generalisable to other villages in West Africa and the region. Second, all entomological experiments were conducted under restricted human-behaviour conditions. Whilst adults in local villages go inside their houses around midnight [64], in our studies they went indoors at 21.00 h to increase mosquito catches indoors. Third, these experiments were conducted under controlled conditions to assess each intervention (height, windows, doors, ventilation) separately, larger entomological trials are necessary to confirm and gather more information. Lastly, the findings of Chapter 7 which discussed the daily routines of the villages from a qualitative perspective might be affected by the uniqueness of the villages where the data was collected and by the closeness of the author with the community members. However, thorough critical analysis was followed during the qualitative data analysis to reduce bias as much as possible.

8.3 Future direction and wider applicability of this research

Recently, the importance of the built environment in health has become evident with the COVID-19 pandemic. Physical infrastructure, however, is not linked to quarantine and pandemic situations alone. In the context of vector-borne diseases houses play a crucial role, especially for diseases where people are mostly infected indoors or in close proximity to dwellings like malaria, Chagas disease or dengue fever [90]. In the tropics and sub-tropics the purpose of a house of providing a comfortable and secure shelter and protecting its inhabitants from external threats is diminished by house design that does not take into consideration entry of disease vectors, like mosquitoes or bugs. Strategies to prevent disease vector house entry, even though simple, are not commonly implemented in poorer homes in the tropics or subtropics. These houses would greatly benefit of self-closing doors, screened doors and windows and the use of more resistant construction materials.

In 2017 the World Health Organisation (WHO) published a policy brief on housing improvements for vector control, the house is portrayed as key for strengthening multisectoral approaches, keeping vectors out and improving living conditions associated to infrastructure [90]. The main strategies in the guidelines are screening windows, doors and eaves, plastering cracks in floors, walls and ceilings when appropriate or placing ceilings as an extra roofing layer. The importance of ventilation to improve human comfort and increase use of bed-nets in hot climates is also emphasised. In summary, keeping vectors out from a house is the core goal of house improvement programmes for vector control. These guidelines are an important step to link housing to health and to expand the understanding of healthy environments. In 2018, however, in the Housing and Health Guidelines there is no mention of the specific risks of vector-borne diseases associated to housing, although it recognizes the importance of housing in disease prevention [99]. The guideline is a document for policy makers at local, regional and national levels and therefore covers general aspects of risks and health challenges associated with house infrastructure. In the section discussing the burden of disease associated with housing there is mention of diseases due to lack of access to water, air pollution or dampness, overcrowding and buildings collapsing but not disease caused by insects or other kinds of vectors. It does not include specific suggestions for vector-borne diseases or for houses located in different climatic zones. More recently, in the Guidelines for Malaria 2021 house screening is given a conditional recommendation due to lack of evidence of the intervention to prevent malaria infections by itself [215]. Focusing this specific strategy only on malaria narrows its impact on broader topics like creating healthier cooking environments when cooking indoors with firewood or in increasing the comfort levels of a house and consequently increasing the chances of people sleeping under a bed-net [3]. It is important to think of the house as a fundamental part of the environment capable of preventing vector-borne diseases.

There are several challenges contributing to this lack of malaria vector control strategies based on the built environment, funding being one of the most important both for research and implementation. In 2020, 619 million USD were invested in malaria related research [1,216], of which 28 % was invested in basic research, 10 % in vector control products and the remaining 62 % in other type of research including vaccine and drugs research and development. In order for infrastructure-based vector control strategies to be accepted and recommended by international organizations their effectiveness preventing disease infection or contributing to vector control should be proved by following high standards that imply financial investment [217]. One challenge major challenge is to translate the results from these studies into real environments. In the Global South it is common that families build and /or live in pieces of land they do not legally own, which makes it is almost impossible for government or non-governmental organizations to build housing projects or to improve the existing ones due to their internal regulations. The investment needed for infrastructure-based vector control strategies is much higher than the 4.50 USD that an ITN continuous distribution costs per person per year [218], but the benefits could be larger too. Infrastructure-based vector control strategies might impact multiple diseases while improving general wellbeing of its inhabitants and lasting longer than conventional interventions. Costs of infrastructure-based interventions can be further reduced by including users in the construction or improvement of their houses at the same time that local communities increase or gain knowledge that could potentially improve their family economy.

This thesis highlights how infrastructure-based strategies can contribute to malaria vector control. The experiments conducted were based on local knowledge (e.g. raising resting places from the ground), common knowledge (e.g. increasing ventilation to improve human comfort) and interaction with other disciplines (i.e. architecture, sustainability). Raising houses, changing roof colour, screening different amounts surface in façade, utilizing passive and active ventilation methods were tested as individual experiments. The studies presented in this thesis individually evaluate the role of elements in house infrastructure for malaria prevention and to increase of indoor human comfort. Previously other house elements like roofs[58], eaves [219] and ceilings [220] have been evaluated, however, there are still elements like walls, floors and their materiality that are yet to be explored. There is additional need to evaluate these elements as a combination and as individual design. Material solutions need to work as an ensemble and in accordance with user-behaviour to guarantee the best possible outcome. Studies with primary users of the household space are needed as well as technical studies on how different materials might work together. In a broader sense of the built environment, infrastructure and space play important roles in vector-borne diseases prevention and studies around human behaviour related to vector behaviour can enlighten how to prevent contact between them.

A study looking at several health and malaria surveys in relationship to housing conditions in sub-Saharan Africa showed that improved housing was associated with malaria protection [61 85]. While it is crucial to improve existing housing, securing it against disease vectors is vital especially with such rapid urban growth. Governments should put in place programs that allow improved housing availability that matches the increasing population numbers in the region.

Since the introduction and success of ITNs, indoor residual spraying and treatment with antimalarials as a combination of strategies for malaria prevention there has been a consistent reduction in cases, 68 % of which are attributed to the use of ITNs [34]. Part of the success of bed-nets for malaria control and prevention is that they are technological improvements on a traditional practice. Before the introduction of ITNs, untreated bed-nets were used in some parts of sub-Saharan Africa, like rural Gambia, to provide privacy to people sleeping in the same room or to prevent insects and small animals disturbance at night [221,222]. Building on existing practices allows groups of people to better adapt to change and to immerse in health practices by slightly altering their health behaviour or the elements related to it. ITNs act partly as a barrier to mosquitoes and provide more ventilation to users than cloth nets because of their screened material [222] and also contribute to the general reduction of mosquito population. Since 2015 there has been a slowdown in the reduction of malaria prevalence deaths in many countries and even a stalling in others [1]. The most mentioned factor for not using an ITN at night was that it was too hot to be comfortable under one [223]. In the future, malaria vector control should be built on a combination of strategies that have been proved successful like housing modification and ITNs. The use of locally sourced materials for housing to keep vectors out construction should also be explored. This would contribute to reducing malaria infection while contributing to climate change as well.

8.4 Recommendations

While architecture and engineering in general terms have advanced considerably since the initial housing experiments by Celli to prevent malaria were conducted in 1901, this development has rarely been done in response to malaria or disease prevention. Some advances have concurred with disease prevention strategies but have not been propelled by them. To reconcile these disciplines there is a need to evaluate the potential of engineering advances in the health sector. The implementation of pilot experiments with housing modifications is a good way of testing designs without a large investment of funding, as long as these follow certain parameters (e.g. randomization) to allow the evaluation of the intervention only. Keeping experiments simple and changing one element at the time is key to detect the effect of the specific house intervention.

Recommendations from the experiments in this thesis include: 1) elevating a house from the ground without closing the space underneath it (ground floor) reduces indoor mosquito density. Although initial results obtained elevating a house without closing the space underneath were promising in reducing indoor mosquito density, they decreased when closing the space underneath with air-permeable or solid layers. Further research is required to assess what would be the use (if any) that users envision of the space underneath an elevated house. 2) painting roofs white reduces indoor temperature and increases human comfort levels. Collected data in this study suggests that painting a roof white can decrease temperature in the room underneath it, the experiments however were conducted in inhabited houses. It would be interesting to conduct a trial with existing houses to evaluate if the same effect is achieved in used and worn metal roof sheets. 3) Screening windows and doors decreases indoor mosquito density and temperature and increases human comfort. Our experiments showed a decrease of indoor mosquito density as a response to increase in screened surface in façade, this was hypothesised as a response to the decrease in carbon dioxide production due the lower temperatures in the house. The experiment, however, could be repeated to assess the impact in mosquito attraction of artificial light, either tungsten or LED, passing through the screened surface and how this might affect results when paired with human behaviour (i.e. people leaving the house at night). 4) Using ceiling fans contribute to reduction of mosquito density and indoor temperatures. The study showed that a working ceiling fan during the night reduced the numbers of mosquitoes collected in the light trap. It is not clear if this was because less mosquitoes entered the house as sleepers produced less carbon dioxide because the house was cooler or because the light trap was located below the fan and they were blown away by the wind it created or more simply, stopped or avoided flying at high wind speeds. Our pilot experiment with the solar chimney, passive ventilation, needs further research on strategies to make the house cooler and to extend the cooling effect of the chimney further into the night. 5) The engagement of different groups of people should be prioritized at specific points of the intervention or research projects. For example, women's opinion during the design process is important as it is more likely they will be the ones interacting the most with a house-based vector control strategy. Since men and elders are the ones officially granting support to projects and interventions, it is important that they clearly perceive the positive impacts the project might have. Even though having the community as a whole is the best strategy for any project to succeed is important to know which groups opinion and participation is more important at certain time to have a better use of the resources and time.

World Health Organization should reincorporate infrastructure-based strategies in the technical documents and guidelines for malaria prevention. These documents should have a section to discuss how to implement elements to prevent house mosquito entry, the effects of this type of interventions and future research needed in the area. The suggestions in these guidelines could be divided into retrofitting and new construction strategies both of which can build on existing houses in good condition and the new housing market. To produce the information needed for writing up the technical documents it is necessary to conduct specific research that can assess each house element separately to identify the best design and materials to be used and consequently conduct studies to assess the elements as a combination. It is also important to provide multiple options, both in design and material to facilitate the adaptation of the strategies to specific markets, geographies and cultures. Social sciences studies should be conducted to assess the acceptability of possible users and to incorporate their feedback in design and selected material. To carry out the studies that can support the contribution of house modification to malaria vector control there is a need of funding specifically intended for this purpose.

West African nations located below the Sahel should join efforts to research and implement malaria prevention strategies based on infrastructure modifications. This could contribute to increase the amount of improved and modern housing in the region and to prevent malaria cases. Because of their geographical location, they share similar climatic and environmental conditions and various ethnic groups that share cultural and social characteristics cross their borders. This set of similarities could allow them to develop housing typologies and housing improvement strategies as a group. It would be interesting to develop house typologies utilizing traditional and local materials improved with technology as means to empower local construction workers, include users in the house construction and reduce dependency from imported goods. Developing an international project aligned with the United Nations goals of improving health and providing safe housing could have a large impact in many aspects and could be expanded beyond the initial countries involved.

The Gambia should increase the offer of its construction market. By introducing variations of goods utilized in construction all over the country they could achieve an impact in other areas as well. For example, in the coast where there are more options available, there might be availability of coloured metal sheets for roofs but in rural areas bare-metal corrugated sheets are the only option. By introducing white or light-coloured roofing sheets in the national market and ensuring that it reaches the rural areas at a competitive price families could purchase it when building their houses or replacing their roofs. An investment that would probably start as a novelty could have impact in the comfort inside the house, their willingness to use bed-nets and therefore in malaria cases. The National Malaria Control Programme could include screened net distribution as an activity in their Insecticide Residual Spraying country wide visits. This could encourage people to screen their windows, increasing the air exchange in rooms and improving human comfort and respiratory health conditions.

Despite the level at which house modification and upgrading might be implemented it is necessary to be aware that it requires multisectoral collaboration and the commitment of a wide range of stake holders. House modification itself and its characteristics have to be approved by the users and owners first. It should be based on research with successful outcomes. It requires a considerable amount of funding, which can come from various actors from government to external organizations and foreign countries. Various ministries or institutions should be involved as well, to ensure the data collection used to measure the impact of the intervention, provide support with market expansion, regulate land ownership or provide an alternative solution to land tenure issues, guarantee the provision of infrastructure services, among others. House improvement or modification should be perceived as one more tool in the fight against malaria, it cannot eliminate malaria by its own but it can contribute and enhance the compliance of other tools like ITNs and IRS.

8.5 Conclusion

Despite the global investment and coordinated effort to control, eliminate and eradicate malaria since 2000, this disease still is a major public health concern in sub-Saharan Africa, despite considerable progress in reducing infection cases and malaria related deaths with the use of ITNs in combination with IRS and improvement of access to health care. This progress, however, is threatened by the poor coverage of interventions, insecticide resistance and inferior nets that do not last long and lose their insecticide content [4] quickly among other challenges associated to geopolitical constrains and worsened by the COVID-19 pandemic [1]. As a response is important to explore alternative strategies that contribute to malaria vector control. House modification for vector-control is a long-term strategy that might contribute by itself in reducing indoor mosquito density and associated bites by endophagic mosquitoes. Housing might promote better use and compliance of other vector-control strategies by providing comfortable indoor spaces that might make people willing to use bed-nets to sleep. Using housing in combination with successful vector control strategies might allow a progressive increase in the reduction of malaria cases and malaria related deaths in sub-Saharan Africa.

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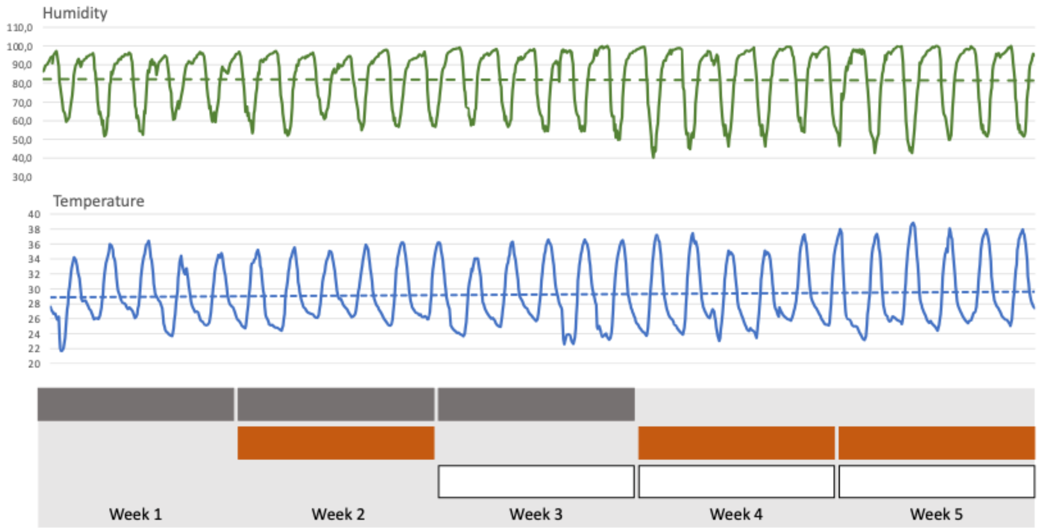
Appendix 1. Total collection of mosquitoes during the study: "The effect of physical barriers under a raised house on mosquito entry: an experimental study in rural Gambia"

	Hut on the ground	Raised hut with open ground storey	Raised hut with air-permeable ground storey	Raised hut with solid walls on ground storey
Female *An. gambiae*	1259	873	981	655
Male *An. gambiae*	1	0	0	1
Female *An. pharoensis*	1	0	0	3
Male *An. pharoensis*	0	0	0	0
Female *An. ziemani*	9	3	5	0
Male *An. ziemani*	1	1	0	0
Female *An. rufipes*	6	0	0	0
Male *An. rufipes*	0	0	0	0
Female *An. funestus*	11	6	4	2
Male *An. funestus*	0	0	0	0
Female *An. squamosus*	6	2	1	2
Male *An. squamosus*	0	0	0	0
Female *Cx. quinquefasciatus*	610	588	645	598
Male *Cx. quinquefasciatus*	22	8	14	19
Female *Cx.thalassius*	34	58	52	45
Male *Cx.thalassius*	2	4	1	1
Female *Mansonia* spp.	8535	4281	5021	4145
Male *Mansonia* spp.	0	1	0	2
Female *Aedes aegypti*	7	3	6	1
Female *Aedes aegypti*	1	0	0	0

Appendix 2. Outdoor temperature and humidity during the study: "Effect of roof colour on indoor temperature and human comfort levels, with implications for malaria control: a pilot study using experimental houses in rural Gambia"

Grey = bare metal roofs, red = red roof and white = white roof.

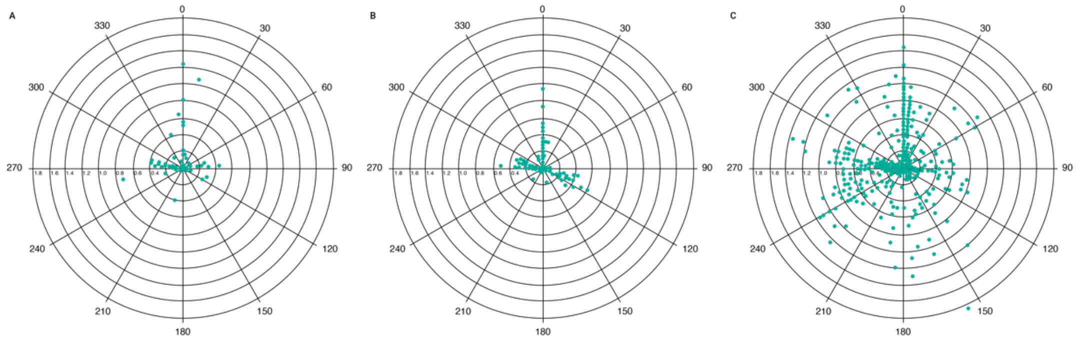


Appendix 3. Total collection of mosquitoes during the study: "Effect of passive and active ventilation on human comfort and malaria mosquito-house entry: an experimental study in rural Gambia"

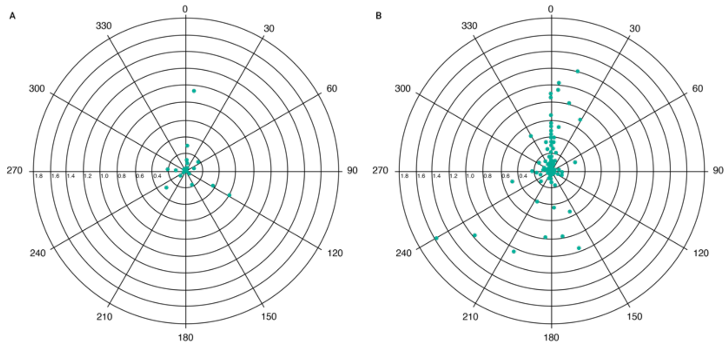
	Solar chimney		Ceiling fan	
	Control	Intervention	Control	Intervention
Female *An. gambiae*	132	114	94	44
Male *An. gambiae*	2	8	2	0
Female *An. pharoensis*	4	4	0	0
Male *An. pharoensis*	1	2	0	0
Female *An. ziemani*	1	2	1	3
Male *An. ziemani*	1	0	0	0
Female *An. rufipes*	0	1	10	4
Male *An. rufipes*	0	0	0	0
Female *An. funestus*	0	1	0	2
Male *An. funestus*	0	0	0	0
Female *An. squamosus*	1	3	1	0
Male *An. squamosus*	1	1	0	0
Female *Cx. quinquefasciatus*	10	15	14	5
Male *Cx. quinquefasciatus*	2	6	2	1
Female *Cx.thalassius*	12	10	18	5
Male *Cx.thalassius*	0	1	0	0
Female *Mansonia* spp.	1008	1231	2197	1272
Male *Mansonia* spp.	0	5	2	1
Female *Aedes aegypti*	3	6	0	0
Female *Aedes aegypti*	0	1	0	0

Appendix 4. Wind speed and direction recorded during the study: "Effect of passive and active ventilation on human comfort and malaria mosquito-house entry: an experimental study in rural Gambia"

Solar chimney



Ceiling fan



Appendix 5. Interview guide for the study: "Household activities of residents in rural Gambia during the rainy season and their implications for exposure to malaria and control: a qualitative analysis."

Changes in Construction

- If this is not the village were you grew up, how it was different from this village in terms of layout organization and household construction and materials?
- When you arrived to this village how was it different compared to now?
- Where houses different in the past? How did they differ from today? (Materials, space use)
- Are all the houses similar in your village? (If there is a house that is different, how?)
- Who is involved in the construction process? (men vs women, family vs community)
- What specific activities do they perform?
- Is there a production process before the actual construction takes place? (e.g. production of bricks)
- Which are the construction times? (In the day and during the year) why?
- In your village, are there specific people that have more knowledge regarding construction techniques than others?
- Are there people that specialize in the construction or repair of different parts of the household?
- How is constructive knowledge transferred in your village?
- If you wished to repair your house, who would you ask for help?

Routine activities

- Can you tell us what time you wake up normally?
- What are the first activities in your day?
- Can you tell us your activities along the day?
- Are there days that are different from others in terms of activities you perform?
- How does leisure time fits in your routine?
- What time do you usually go to bed? Are others going to bed at the same time?
- How does your routine changes between the dry and rainy seasons?

- Can you tell us about any activities that you participate with people of your same gender only?
- Can you tell us how household chores are divided among members of the family?
- Who is in charge of care activities in the household?

Response to change

- If you had to build a raised house which would be your main concerns?
- If you were asked to build a raised house what materials would you use?
- Do you think there are local materials that could be used to building raised houses?
- Do you think different groups of people would have different concerns to living in a raised house? (e.g. specific concerns of elderly or young children)
- If you had screened doors, which would be your main concern?
- If you had screened windows, which would be your main concern?
- In which changes to make your house cooler would you invest?
- If you have slept in a thatched roof house, how is it different from a corrugate roofed one?