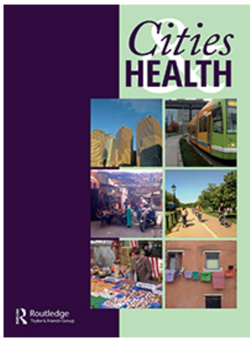

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REFLECTIVE PRAXIS – THINK PIECE

Research agenda for preventing mosquito-transmitted diseases through improving the built environment in sub-Saharan Africa

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ABSTRACT

Mosquito-transmitted diseases are a major threat to health in sub-Saharan Africa, but could be reduced through modifications to the built environment. Here we report findings from a major workshop held to identify the research gaps in this area, namely: (1) evidence of the health benefits to changes to the built environment, (2) understanding how mosquitoes enter buildings, (3) novel methods for reducing mosquito-house entry, (4) sustainable approaches for reducing mosquito habitats, (5) case studies of micro-financing for healthy homes and (6) methods for increasing scale-up. Multidisciplinary research is essential to build out mosquito-transmitted diseases, and not build them in.

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Introduction

In sub-Saharan Africa (SSA), mosquito transmitted diseases are a serious threat to health, well-being and economic development (WHO 2017). The two biggest disease threats are malaria and arboviruses (viruses transmitted by arthropods) including dengue. Malaria is transmitted by *Anopheles* mosquitoes, that are rural night-time biting vectors, whilst many important viral diseases like dengue, chikungunya, yellow fever and Zika are transmitted principally by *Aedes aegytpi* mosquitoes, which are urban day-biting vectors. Both malaria and *Aedes*-borne diseases are environmental diseases affected by the quality of the built environment, with the majority of mosquito biting occurring inside or around houses, and most of the aquatic habitats being man-made (Zahouli *et al.* 2017).

Since 2000, huge progress has been made in reducing malaria in SSA, with the proportion of people carrying malaria parasites halved between 2000 and 2015, and clinical episodes declining by 40% (Bhatt *et al.* 2015). This major public health achievement has been due largely to vector control, with massive deployment of long-lasting insecticidal nets and indoor residual spraying. Progress, however, has faltered, and the ten highest burden countries in Africa reported increases in cases of malaria in 2017 compared with 2016 (WHO 2018). Today, malaria remains a major public health problem in the region with 183 million cases in 2017 and 545,000 deaths (Weiss *et al.* 2019). Despite this hiatus, there is a commitment to eliminate the disease in one generation (Feacham *et al.* 2019). In order to do this, additional methods of control are required to facilitate elimination and keep malaria out after elimination. Changes to the built environment would contribute massively to achieving this laudable goal.

Dengue is one of the fastest growing pandemics in the world, and the number of global cases has increased 30 fold over the past 50 years (https://www.who.int/denguecontrol/epidemiology/en/). There are estimated to be 390 million cases worldwide each year, but there is considerable under-reporting (Stanaway *et al.* 2016).

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We are uncertain of the true number of cases of dengue in SSA (Amarasinghe *et al.* 2011, Were 2012) since until recently, most fever cases were considered to be malaria. It is clear though that dengue is being transmitted in the region and *Ae. aegypti*, is common in African towns and cities (Agha *et al.* 2017). As urban areas expand it is highly likely that *Aedes*-borne diseases will become more common in SSA, unless action is taken to reduce the aquatic habitats of the immature mosquitoes (Abílio *et al.* 2018) and reduce the number of adult biting mosquitoes, since there is no dengue vaccine suitable for programmatic use or any specific treatment.

Control of the mosquito vectors of malaria and arboviruses remains the mainstay of reducing the threat, alongside prompt and effective diagnosis and treatment. However, there are two neglected approaches to control. First, mosquito-proof housing to reduce exposure of humans to potentially infectious bites while indoors. Second, reducing the number of mosquitoes in the peri-domestic environment by removing water bodies where the mosquitoes that transmit disease lay their eggs and the immature stages (the larvae) develop. Both of these methods require appropriate design, construction and management of the built environment. For *Anopheles gambiae*, the principal malaria vector, this can be done by improving drainage and removing aquatic habitats in rural and peri-urban areas. For *Ae. aegypti*, the world's best transmitter of arboviruses (viruses transmitted by insects and ticks), the mosquito larvae are found in water-storage containers, discarded plastic or other waste receptacles, car tyres, blocked guttering, flower pots, underground drains or septic tanks and a plethora of other clean water aquatic habitats that abound in towns and cities. Populations of *Ae. aegypti* can be reduced by the provision of reliable piped water, removing these containers through effective solid waste management and community engagement and by designing infrastructure that does not collect water (Lindsay *et al.* 2017).

Between 2000 and 2015, there has been a marked transformation of housing in urban and rural SSA with a doubling in the proportion of improved housing (Figure 1) (Tusting *et al.* 2019). These changes have occurred without specific intervention, largely resulting instead from individual households investing in their homes. There were, however, 53 million Africans living in urban slums in 2015. As the housing market expands during this century, the drive for better housing is a major opportunity to introduce vector control measures along with other improvements. With the population of Africa expected to increase from 1.3 billion people today to 2.4 billion in 2050 (https://www.worldometers.info/world-population/africa-population/), there has never been a better opportunity to help make human settlements healthier.

Recently it has been acknowledged that we must rely less on insecticide-based approaches and adopt multisectoral strategies to control mosquito transmitted diseases (WHO 2017). In 2015 Roll Back Malaria, the United Nation's (UN) Development Programme and UN-Habitat produced a consensus statement (Roll Back Malaria, UN Development Programme, UN Human Settlements Programme 2015) outlining the key research questions that should be addressed to help reduce the threat of VBDs through housing improvements. Since then research in this important area has expanded and the focus has been broadened to the built environment, not just housing. The BOVA

Figure 1. Large scale newbuilds replacing slums in Kibera, Nairobi.

(**B**uilding **O**ut **V**ector-borne diseases in SS**A**, https://www.bovanetwork.org/) Network is an international coalition of researchers and practitioners from the health and built environments and is funded through the UK government's Global Challenges Research Fund (GCRF). The aim of the Network is to establish an entirely novel research area in vector control that exploits improvements in the built environment to develop sustainable and resilient communities free of mosquito transmitted diseases. The network recognizes the value of multisectoral approaches necessary to scale up safe and affordable housing in rural and urban communities.

Here, we report the conclusions of a major workshop, the second BOVA Open Network Meeting, held at the UN-Habitat headquarters in Nairobi, Kenya on 4–5 April 2019 (Figure 2). We identified the most important areas for future research through a series of collaborative workshops with experts from the built environment and health. The discussions were recorded and combined to develop a research agenda required to strengthen the control of mosquito transmitted diseases in SSA through improvements to the built environment. Our findings are outlined below. Whilst our focus is on Africa, these research gaps are also applicable to other parts of the tropics.

Advocacy

In the world's first housing and malaria consensus statement it was stated that 'there is compelling evidence that housing improvements enhance protection of residents from vector-borne diseases' (Roll Back Malaria, UN Development Programme, UN Human Settlements Programme 2015). The evidence for improving housing to reduce malaria was systematically reviewed in 2015 (Tusting *et al.* 2015), with another follow-up review for malaria in progress (Furnival-Adams *et al.* 2019). Since such formal reviews are a powerful way of providing evidence of the efficacy of interventions to policy makers, there is an urgent need for similar reviews to make the case for improved housing also being protective against other insect and tick transmitted diseases. In particular, it was recommended to draw on grey literature and reports of organisations working on housing interventions, which may not fall within typical search areas for systemic reviews. Furthermore, to support the development of high-quality evidence, tool kits that employ best practice methodologies should be developed for the assessment of current vector risks in the built environment and to evaluate the effectiveness of interventions.

In the first half of the twentieth century engineering solutions to malaria, such as drainage and house screening, were firmly engrained in malaria control operations (Watson 1921, Home 1926, Gilroy 1948), but since then much of this knowledge has been lost, and today, in most vector control programmes, there is little in the way of environmental management (Wilson *et al.* in press). Cross-over between disciplines should see the concept of healthy housing taught from school age through to professional training of entomology/public health, architecture, and design students. Interdisciplinary curricula development and course content would help transform teaching of this important topic.

In order to develop research in this area, a platform to link different practitioners and professionals is vital to ensure the cross-pollination of ideas and collaborative projects to implement built environment solutions for mosquito transmitted disease control. Although the BOVA Network sets out to bring together those who work on mosquitoes and the built environment, more work is required to strengthen this relationship and make it sustainable. In particular, there is a need to attract other practices, such as building developers, and expand the Network to share knowledge, expertise, and experience across professions. Expanding advocacy on positive impacts of improved housing, will ensure greater considerations in policies for control of important diseases such as malaria.

Basic research on vectors & the built environment

Remarkably little research has been done on mosquito behaviour in and around the home. This is surprising given that up to 80% of malaria transmission in SSA

Figure 2. BOVA Network management board at UN-Habitat, Nairobi.

occurs indoors at night (Sherrard-Smith *et al.* 2019) and *Ae. aegypti* spends its life in or around buildings. Clearly, a better understanding of how disease transmitting mosquitoes move in this built environment would be illuminating. Recent experimental studies with rural African houses have demonstrated marked differences in the number of mosquitoes entering different typologies of houses (von Seidlein *et al.* 2017, Jatta *et al.* 2018). The reasons for the variation in mosquito-house entry is due to the human odours that leak from a building and the porosity of the structure. Mosquitoes are attracted to a house by host cues such as carbon dioxide and human odours that emanate from an occupied building at night (Takken and Knols 1999). The form and concentration of these emissions is shaped by the number and age of the people in the house, indoor and outdoor climates, as well as the materials used for house construction and the house design. Computer simulations of airflow, based on these variables could be used to better model how attractive odours leak out of houses and thereby draw mosquitoes indoors (Figure 3) (von Seidlein *et al.* 2019). This approach should be combined with studies on the 3-dimensional flight of mosquitoes to improve our understanding of mosquito house entry.

An important adjunct to this research is to better understand human behaviour in and around the house that will have an impact on mosquito biting. This includes when people go indoors at night and when and how frequently they open the doors and windows of a house. Detailed studies have identified the critical indoor temperatures at which most people feel comfortable (thermal comfort zones) (Fanger 1970), houses should be designed to take these into account. Combining field, laboratory and theoretical studies is likely to provide important insights into how to reduce mosquito house entry.

New tools and approaches

The World Health Organization's main publication on environmental management for mosquito control published in 1982 (WHO 1982), recommends using a screened door – based on a design published in 1928! (Coogle 1928) We can surely do better than that? Developments in building materials and new designs offer exciting, creative and effective opportunities for excluding mosquitoes and incorporating housing concepts which can improve health and well-being in general (von Seidlein *et al.* 2019). Recent research has tested new ventilated doors (Figure 4) (Jawara *et al.* 2018) and new types of screened houses (von Seidlein *et al.* 2017), made from lightweight materials with a low thermal mass to help keep the house cool at night so that people are more likely to sleep under an insecticide-treated net (Pulford *et al.* 2011). Since the vectors of malaria and *Aedes*-borne diseases have different breeding sites interventions to reduce them are likely to differ. For malaria control in rural and peri-urban areas, innovations in land drainage needs to be considered to reduce the accumulation of surface water, which creates aquatic habitats that are suitable for mosquito larvae. For *Aedes* control, innovation in mosquito-proof water storage containers is required, as is the facilitation of solid waste removal and community engagement. Multiple interventions will be required to reduce the transmission of mosquito transmitted diseases.

There is considerable opportunity to develop new materials such as tear-proof mosquito screening and new types of self-closing ventilated doors. Building materials should be durable, have a low thermal mass and low carbon footprint, and where possible, be locally sourced. Construction of prototypes is important to test new ideas and technologies and to assess the acceptability of interventions. A review could be undertaken of house designs which are available today, are in harmony with human needs and are

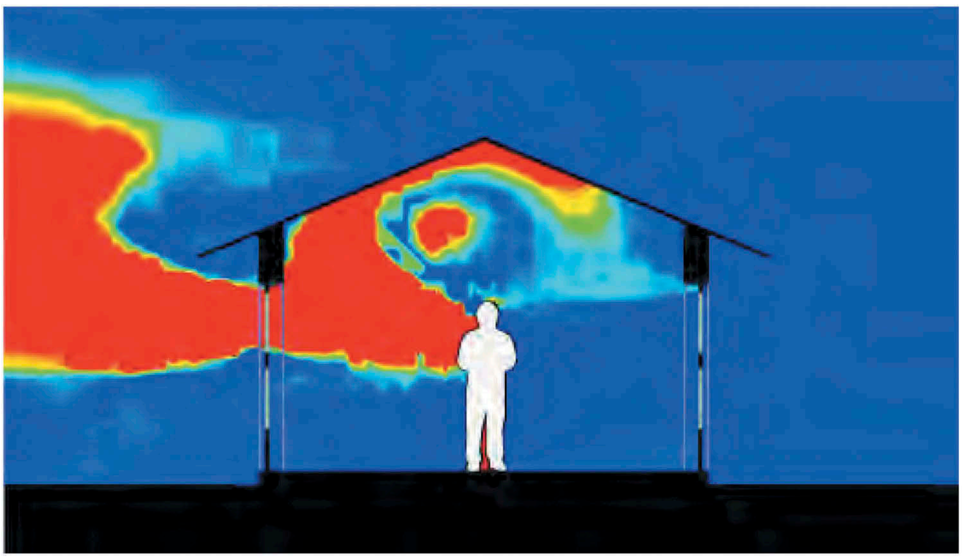

Figure 3. Carbon dioxide emissions modelled using computer fluid dynamics.

Figure 4. Prototype mosquito-proof door which allows ventilation.

scalable. Having established 'what is out there', these should be tested and evaluated to demonstrate protection against mosquitoes. House design and materials should, of course, be considered in relation to the cultural setting, including an understanding of what people desire of their homes, and how people use the space both inside and immediately outside their houses. Ultimately updated guidelines need to be produced that include well-tested approaches that can be employed in different settings.

Although much of the narrative is about protecting people in their home, transmission of both malaria and *Aedes*-borne diseases can occur immediately outside the house. Solutions for protecting people in this space have been poorly explored, and there is an opportunity to re-invent the screened porch or develop a safe space for people to sit outdoors without being bitten by mosquitoes. Preventing outdoor biting becomes more important when effective vector control interventions like insecticide treated bednets or indoor spraying of insecticides reduces indoor biting to very low levels. Evaluation of the impact of safe outdoor spaces on disease is essential. Overall, mosquito-borne diseases are strongly driven by surface water and poor housing. The most impactful innovations will therefore be those that accelerate acquisition and scale-up of safe housing and environments.

Scale-up

Research is needed to help identify the most effective methods for scaling-up healthy homes. In SSA there are numerous innovative solutions to finance house construction, with different products targeted according to the person's ability to pay (https://www.habitat.org/impact/our-work/terwilliger-center-innovation-in-shelter/shelter-solutions-for-people-in-sub-saharan-africa, http://housingfinanceafrica.org/). For example, in Uganda a number of micro housing financing initiatives have been rolled out to support improvement of healthy homes. Finance institutions such as Finance Trust bank, Centenary bank, Pride Microfinance and others have developed 'home improvement loans'. Housing organizations such as Shelter and Settlements Alternatives: Uganda Human Settlements Network (SSA: UHSNET), Habitat for humanity, ACTogether and Uganda Housing Cooperative Union are working with financial institutions to target community members and groups to access these products. These loans are now being used by low income earners to improve the ventilation of existing housing, adopt clean energy through solar and clean cooking, improve access to safe water and sanitation, purchase insecticide treated bednets for the prevention of malaria and improve the housing structure (plastering and screening or tiling floors). In order to scale-up these housing improvement packages, communities have been mobilized into housing cooperatives and savings groups to increase the portfolio to the financial institutions. Sustainability can be built into projects if ways can be found to control mosquito transmitted diseases and generate income at the same time. One of the BOVA pump prime projects 'Trash to Treasure', has individuals collecting waste bottles, buckets and tyres, all potential mosquito breeding sites for *Ae. aegypti*, and then sells the trash for recycling (Figure 5). Financial benefit and/or increased prestige should motivate people to stay engaged with a project.

Joint delivery between health-care providers, other public services and house builders should be explored to identify case examples of good practice, and focus on incremental approaches where households are supported to create healthy mosquito-proof homes. There is also a need for research to help address the construction skills gap and build capacity. Organisations such as Tanzania's Vocational Education and Training Authority (https://www.veta.go.tz/) are already working in this area, but more needs to be done to better understand whether such models could be rolled out in other African countries. New technologies can also play a role here. For example, iBuild (https://www.ibuild.global/) is a mobile phone platform connecting those in need of shelter with construction teams and housing support services. There may also be local building regulations that could be used to help build healthier

Figure 5. Trash to treasure plastic for recycling.

environments. What these are and how they could be enforced remain largely unknown in the field of healthy homes. Moreover, care must be taken to consider both rural and urban settings and the unique challenges faced.

It will be essential to widen the dialogue and learn from successful case studies. For example in Singapore a highly organised and successful dengue control programme relies predominantly on environmental management (Figure 6), and in Cambodia natural vector control of dengue through guppy fish production in households is now extended to schools and health centres in Kampong Chan region (Kumaran *et al.* 2018).

Community-based approaches

Community-based research is essential to develop and maximise the uptake of new interventions, particularly at a household level (Andersson *et al.* 2017). The community includes all those with an interest in, and impacted by a particular project, from decision-makers and policy designers to those who live in new or modified houses, as well as architects, designers and neighbours. With all interventions, communities should be engaged in the planning stages and throughout the life of the project since they have important knowledge and information to contribute, and their

Figure 6. Environmental management_construction site Singapore.

engagement will give them ownership of research and initiatives that directly affect them. Communities will also need to be informed about interventions and, in some cases, behavioural changes may be necessary. Identifying the key actors in the community is important, and investigators should take care not to inadvertently impose 'artificial' communities by having preconceived ideas of who to involve. Often those most directly affected by a problem are those with the least economic resources, but it is important that they have a voice in decision making, and they can often make a valuable contribution. Besides, low-income households often have competing priorities that inhibit meaningful improvements of housing and environments. 'Positive deviants' (PD) are individuals who have the same resources available to them as their neighbours, but who have nevertheless come up with novel solutions (Nieto-Sanchez *et al*. 2015). Their ingenuity should be harnessed through the development of exchange and sharing plans. While the scale-up of PD interventions across communities and countries is not without its challenges (Albanna and Heeks 2019), learning from the experiences of others from similar but disconnected contexts and dissemination of effective practices is presently under-utilised. Beyond these, it may be necessary to partner with other stakeholders such as those with special knowledge or influence in a community, government or local authorities. The means of communication needs to be tailored to the audience (policy-makers, decision-makers, manufacturers, health professionals, urban planners, students, communities, etc.).

The community's knowledge of health, housing and cost issues should be considered and their priorities should be central to the research aims and objectives, since ultimately the building material, durability, structure and design may all influence community acceptance and adoption of a project. For projects trying to reduce mosquito breeding sites in the built environment there are established guidelines on social mobilization and communication, at least for *Aedes* control (Parks and Lloyd 2004).

Although community-based participatory research or participatory action research provides established methodologies for community-based research, new methodologies are continuously being developed which may prove to be highly suitable for working in the area of mosquito transmitted diseases and the built environment. Whatever interventions are developed, they must be developed closely with the target communities. Case studies of where this has been done successfully would help facilitate the research.

Potential funding sources

Finally, an important question not directly addressed in the discussion of research priorities, is where to seek funding for this type of research. In the past, inter-disciplinary proposals have missed out on funding because they did not fit neatly into any one category. Fortunately there is an increasing recognition of the value of an inter-disciplinary approach and there are now calls specifically targeting cross-sectoral research a good example being GCRF funding of the BOVA Network. Aspects of housing-health could be captured under the umbrella of the 'one-health' concept that aims to be broader in scope.

As well as traditional funders of research such as the Bill & Melinda Gates Foundation, Biotechnology and Biological Sciences Research Council, Department for International Development, Economic and Social Research Council, Medical Research Council and The Wellcome Trust, there are other potential sources of funding. For large scale development projects funded by international financial institutions, such as the African Development Bank, it may be possible to add technical assistance/advisory projects on to larger loans or investments. In some cases they might fund a grant for a specific research or pilot project. The philanthropy world is broad, and there are those that focus on urban issues e.g. Children's Investment Fund, Bloomberg as funders of C40. There is also a growing movement of so-called 'impact investing', whereby the primary objective of the investor is not profit but 'making a difference' and improving lives, see http://www.ifc.org/wps/wcm/connect/Topics_Ext_Content/IFC_External_Corporate_Site/Impact-Investing released by the International Finance Corporation in April 2019 and the Impact Programme http://www.theimpactprogramme.org.uk/ which is an initiative of the Department for International Development (DFID). The Centre for Affordable Housing Finance in Africa (CAHF) http://housingfinanceafrica.org/is an independent think tank working to support and grow housing markets in Africa. CAHF publish a Housing Finance in Africa Yearbook (http://housingfinanceafrica.org/resources/yearbook/) which is a useful resource for identifying potential funding sources. Major funders include CitiesAlliance https://www.citiesalliance.org/and the Overseas Private Investment Corporation (OPIC) which is a U.S. government agency, which helps American businesses invest in emerging markets.

Conclusion

With a future vision of an Africa free of malaria and a growing threat of arboviral diseases in African towns and cities there has never been a better time to reassess the role of the built environment in controlling mosquito transmitted diseases. Preventing entry of mosquitoes into houses and reducing mosquito breeding sites offer creative new opportunities for disease control while at the same time improving the living environment of people across the continent. Research into improving the built environment to reduce the burden of mosquito transmitted diseases requires a multidisciplinary approach with experts from widely disparate backgrounds that need to speak a common language. This research should be led or partnered with African researchers, sharing knowledge in both directions and building research capacity in the region. There is enormous scope to produce innovative solutions in the built environment to reducing the threat from mosquito transmitted diseases in villages, towns and cities across Africa.

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Notes on contributors

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