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Recommendations for building out mosquito-transmitted diseases in sub-Saharan Africa: the DELIVER mnemonic

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In sub-Saharan Africa, most transmission of mosquito-transmitted diseases, such as malaria or dengue, occurs within or around houses. Preventing mosquito house entry and reducing mosquito production around the home would help reduce the transmission of these diseases. Based on recent research, we make key recommendations for reducing the threat of mosquito-transmitted diseases through changes to the built environment. The mnemonic, **DELIVER**, recommends the following best practices: (1) **D**oors should be screened, self-closing and without surrounding gaps, (2) **E**aves, the space between the wall and roof, should be closed or screened, (3) houses should be **L**ifted above the ground, (4) **I**nsecticide-treated nets should be used when sleeping in houses at night, (5) houses should be **V**entilated, with at least two large screened windows to facilitate airflow, (6) **E**nvironmental management should be conducted regularly inside and around the home and (7) **R**oofs should be solid, rather than thatch. **DELIVER** is a package of interventions to be used in combination for maximum impact. Simple changes to the built environment will reduce exposure to mosquito-transmitted diseases and help keep regions free from these diseases after elimination.

This article is part of the special issue on novel control strategies for mosquito-transmitted diseases.

Introduction

Over 80% of the world's population is threatened by at least one disease transmitted by insects or ticks, with 50% threatened by two or more [1]. These diseases represent 17% of the global burden of infectious diseases and kill over 700,000 people each year [2], with much of the impact occurring amongst the poorest of the poor in sub-Saharan Africa. In this region, our two greatest concerns are the mosquito-transmitted diseases: malaria, which is a parasitic disease transmitted by *Anopheles* mosquitoes, and *Aedes*-transmitted diseases, including dengue, yellow fever, Zika and chikungunya, transmitted by the world's most efficient transmitter of viruses, *Aedes aegypti*.

Since the turn of the millennium, a concerted campaign of malaria control has halved the proportion of those infected with malaria parasites in Africa [3]. Malaria, however, continues to be a major drain on the health of Africans, as 93% of the global malaria burden occurs in sub-Saharan Africa [4]. In 2018, there were still 213 million cases of malaria and 380,000 malaria-associated deaths in sub-Saharan Africa, and it is becoming clear that our current arsenal of weapons that include insecticide-treated bednets (ITNs), indoor residual spraying and prompt and effective treatment with antimalarials is insufficient to achieve malaria elimination from the region. Among the many health benefits, [5] improved housing can be an additional tool to help achieve malaria control and elimination, and reduce the opportunities for re-emergence after elimination.

As malaria has declined in the region, dengue is rising in importance, predominantly affecting urban populations [6], unlike malaria, which is essentially rural or restricted to the greener parts of African towns and cities. This is due to the differing habitat preferences of the different mosquito species. Dengue is the fastest increasing infectious disease in the world and the number of estimated global cases has risen sharply from 8.3 million reported cases in 1990 to 58.4 million in 2013 [7] due to rapid urbanisation, increasing movement of goods, and, to a lesser extent, climate change. Today, the World Health Organisation (WHO) estimate that there are 390 million cases of dengue globally each year [8]. The true extent of dengue in sub-Saharan Africa is unknown due to weak surveillance and inadequate diagnosis. From 1960-2010, 22 countries reported dengue outbreaks in the region [9], and, more recently, there have been outbreaks reported in Benin, Cote d'Ivoire, Senegal and Tanzania [8], countries previously not reporting dengue infections. It is clear that dengue is increasing its range and outbreaks are becoming more severe in sub-Saharan Africa.

Other viruses transmitted by *Ae. aegypti* are also common in sub-Saharan Africa. A major epidemic of yellow fever occurred in Angola and the Democratic Republic of the Congo (DRC) from December 2015 to November 2016, resulting in 7,334 suspected cases and 393 deaths [10]. A follow-up study to a yellow fever outbreak which took place in Ethiopia from 2012-2014, showed that in 2017 entomological risk indices classified most sites as "high risk" for future outbreaks under current WHO criteria [11]. In 2018, Zika was circulating in Angola, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Côte d'Ivoire, Gabon, Guinea Bissau, Nigeria, Senegal and Uganda [12]. Recent outbreaks of chikungunya have been reported in the DRC with 6,149 suspected cases between January and April 2019 [13]. Other outbreaks of chikungunya (Makonde for 'bone crushing pain') were reported by WHO; in Sudan and Kenya in 2018. All these outbreaks are likely to be underestimated, due to the limited detection capacity of the existing surveillance systems in most countries in sub-Saharan Africa.

Improvements to the built environment offer new opportunities for control of both malaria and *Aedes*-transmitted viruses, and these interventions are timely for two principal reasons. Firstly, Africa's population is expanding rapidly. Between 2019 and 2050, the United Nations forecast that the population of sub-Saharan Africa will double, from 1.07 billion people to 2.1 billion [14]. Millions of new homes have to be built to accommodate the growing population and replace many existing dwellings. Secondly, the economy of Africa has strengthened in recent years. The International Monetary Fund forecast that in 2020 the region will have the second fastest growth rate in the world [15], providing the economic catalyst for building better houses. A recent analysis of housing in sub-Saharan Africa provided evidence that improvement of the housing stock is underway. From 2000 to 2015, the percentage of good housing (with improved water and sanitation, sufficient living area and constructed from durable material) in the region doubled from 11% to 23% [16]. These improvements in housing may have contributed to a reduction in malaria since a recent systematic review of over 15,000 publications showed that residents of modern housing had 47% lower odds of malaria infection and 45-65% fewer malaria cases than those in traditional homes [17]. Additional support comes from an analysis of 29 national health and demographic surveys of 284,00 children in sub-Saharan Africa from 2008 to 2015 [18]. Across all surveys, there was a 9-14% reduction in malaria infection in children living in modern housing compared to traditional ones, after adjusting for household wealth and other factors. Considering that more than 180 million malaria cases are still occurring annually in Africa such benefits could result in between 16 and 35 million malaria episodes avoided. There has never been a better time to influence the design of houses and the built environment to help reduce the transmission of mosquito-transmitted diseases.

Most of us think of our home as a place of sanctuary, yet for mosquito-transmitted diseases, like malaria and *Aedes*-transmitted diseases, the opposite is true for many traditional households. In sub-Saharan Africa ~80% of malaria transmission occurs indoors at night [19, 20], whilst for *Ae. aegypti*, transmission occurs in and around buildings, during the day. For both diseases, the nidus of infection is in or outside buildings. Since much of the biting, and hence disease transmission, occurs indoors, it is important to understand that the risk of being bitten depends on both the extent and position of entry points into a building, as well as the quantity and shape of host odours emanating from a house at night [21]. It is the cues in host volatiles, notably carbon dioxide that mosquitoes use to locate an individual (Figure 1). The ease with which a mosquito enters a building is dependent on the number of occupants in a dwelling, the indoor climate, geometry and materials used for building a house and the extent of any openings [22, 23]. We illustrate that in a poorly ventilated and hot metal-roofed house (Figure 1A) carbon dioxide produced by a sleeping person disperses out of the open eaves, whilst a house that is well-ventilated and cooler (Figure 1B), produces less carbon dioxide, attracting fewer mosquitoes indoors.

Figure 1

DELIVER

This manuscript is written for experts in mosquito-transmitted diseases and those in the built environment (Box 1). It provides recommendations for constructing mosquito-proof houses and keeping neighbourhoods free of those species of mosquitoes that transmit malaria in sub-Saharan Africa and *Aedes*-transmitted diseases through their bite. Our recommendations are crystallised in the mnemonic, DELIVER (Figure 2), and here we provide evidence supporting each one.

Box 1

Figure 2

DOORS

In rural Africa, most doors are not constructed to fit tightly, allowing for good air flow and also mosquitoes to enter buildings. Studies using experimental houses (Box 2) in The Gambia showed that appreciable numbers of mosquitoes enter houses where the only openings in the building are narrow horizontal slits (to simulate poorly-fitting doors) above and below a front and back door [24], and that *An. gambiae* can enter a house through the gap at the top of doors as readily as those on the bottom. Similar findings were made by Bill Snow in The Gambia who found that *An. gambiae* entered small slits in experimental huts at either ground level or eaves level (i.e. 1.72 m) [25]. In marked contrast, far fewer culicine mosquitoes (a group of mosquitoes, none of which transmit malaria) enter a house where the only entry point is a slit at the top of the door (*Culex* spp. = 60%, 95% confidence intervals, CI = 44-76%, *Mansonia* spp. = 31%, 95%CI = 10-46%), compared to houses with gaps at the top and bottom of the door. Clearly, all gaps in a house need to be closed or screened to prevent mosquito entry.

The WHO's 1982 manual on environmental management [26] and the 1997 guide to vector control [27] provide guidance on constructing a screened door, based on an original design from 1947 [28]. This door was used in a randomised controlled trial in The Gambia, where 200 houses were randomly allocated screened doors and had their eaves closed with mud (see next section for more on eaves) and 100 houses left with their original doors and open eaves [29]. The trial demonstrated that screened doors and closed eaves were associated with a 59% reduction in malaria mosquito numbers and, more importantly, a 47% (95% CI =3-71%) reduction in the risk of children being anaemic, compared with traditional houses. Lacking red blood cells (anaemia) is associated with chronic malaria infections and is a major cause of mortality in children under two years old, so theoretically if screening was scaled-up, it could have the potential to reduce malaria deaths.

Recently, wood has become an expensive commodity in Africa, and doors constructed from steel, PVC or aluminium can be cheaper than wooden doors. A recent trial of screened steel doors in The Gambia, however, found that many of the screens embedded in the doors were easily damaged, and hence no longer protected people from malaria mosquitoes (M. Pinder unpublished data). For this reason, new prototype screened doors, more robust and made entirely of metal [30], were designed to allow air to pass through 1.61 mm diameter holes in the door, hence allowing ventilation in the house, but preventing access to mosquitoes. Four types of prototype screened doors were randomly allocated to houses in a Gambian village and compared with traditional doors. All types of screened doors reduced the number of mosquitoes entering houses by 59-77% compared with houses without the new doors.

One important feature of the new screened doors was that they had springs in the hinges which made the doors self-closing, to maximise protection through the night. Keeping the doors closed in the evening and at night in hot environments is, however, not without problems. Some house owners prefer to keep the doors open until late in the night to allow the house to cool from the heat of the day and for people to readily enter houses in the evening. Data loggers fixed to the front and back doors in village houses showed that the period between sunset and midnight is particularly busy [30]. In some households people also thought that keeping the doors open allowed 'good luck' to enter. It is also true for many societies that shutting or locking the house might indicate that householders have something to hide or seem unwelcoming to other community members. This, however, is not normally an issue where people leave their homes to work in the fields during the day or in many urban situations where the fear of thieves means that most houses are well secured throughout the day and night.

EAVES

The main entrance for *An. gambiae* into traditional houses is through the open eaves, the gap between the top of the wall and the over-hanging roof (Figure 1). Observational studies from The Gambia [22, 31] and Uganda [32] showed that houses with open eaves had more malaria mosquitoes than those with closed eaves, and that there was less malaria in houses with closed eaves than open ones [32, 33]. Stronger evidence comes from three experimental studies. The first was a cross-over study in The Gambia using 12 thatched-roofed village houses with open eaves. In the first period, six houses were randomly selected, and their eaves closed. Mosquito collections were made in all study houses eight times in four weeks. In the second period, the intervention was swopped over, such that the six houses with open eaves were closed and the six that were closed, opened, and mosquito collections made as before. Over the study period, closing the eaves was associated with 65% fewer malaria mosquitoes, but no reduction in culicine mosquitoes. In a recent study using experimental houses (Box 2), closing the eaves of thatched houses resulted in 94% (95% CI = 89–97) fewer malaria mosquitoes and 43% (95% CI = 23-58%) fewer culicine mosquitoes than with open eaves. The third experiment was done using experimental huts in Tanzania [34], where screening the eaves reduced entry of malaria mosquitoes. These findings are further supported by those of Bill Snow in The Gambia who found that *An. gambiae* and *Mansonia* spp. were only slightly affected by the wall height, whilst more mosquitoes that usually live outside human dwellings, including *Aedes* spp., *An. pharoensis*, *Culex poicilipes* and *Cx. thalassius*, showed a marked exclusion with increasing wall height from 0 to 1.72 m [25]. Closing the eaves of a traditional rural house is a cheap and simple method for reducing the house entry of malaria mosquitoes. Health promotion by the National Malaria Control Programme in The Gambia has resulted in far fewer houses with open eaves houses in the rural areas of the Upper River Region than in the past (E. Jatta personal communication). The problem is though, that closing the eaves reduces ventilation and can make the house hotter by 0.5 °C between 19.00-23.30 h, when most people are going to bed [23], thereby decreasing the likelihood of bednet use. Screening the eaves would be a better solution, since it would have less of an impact on ventilation reduction.

Many rural houses in sub-Saharan Africa do not have ceillings and the roof material is open to the roof. The presence of ceilings, however, has an effect similar to closing the eaves. Ceilings reduce the entry of *An. gambiae* into homes, since if they enter the house through open eaves, they cannot enter the rooms below through an intact ceiling [29, 35]. In a systematic review of the association between house design and malaria, the presence of a ceiling was associated with a third reduction in the odds of clinical malaria [17]. Closing the eaves and/or adding ceilings to houses will reduce house entry by malaria mosquitoes.

LIFTED

Between 450-420 BC, Herodotus described Egyptian fishermen living near marshes sleeping on raised platforms to escape the bites of mosquitoes [36]. And, at the turn of the 19th Century, it was recommended that houses near Rome should be raised off the ground, and two storey buildings built with the bedroom on the top floor to avoid mosquito bites [37]. Studies of mosquito behaviour over the past 50 years suggest that both historical anecdotes describe adaptations to avoid mosquito bites. In the 1970s, a series of pioneering studies exploring the height at which mosquitoes fly above the ground were carried out using suction traps placed at different heights on scaffolding towers placed over different terrain in The Gambia [38-40]. Although some culicine mosquitoes are frequently found at all flight levels up to 8 m, most mosquito species fly close to the ground, with 80% of the flying population found below 1 m in height [39]. This work suggested to Gillies and

Wilkes that placing circular mosquito-proof fences around people alone or inhabited buildings might be protective [41]. Their findings, however, showed that mosquitoes flew over the 6 m high fences, and provided little, if any protection. Nonetheless, recent studies in The Gambia showed that if there is no fencing guiding the mosquitoes upwards, raising houses above the ground would reduce mosquito house entry and hence disease transmission (M. Carrasco-Tenezaca unpublished data). The principal malaria mosquitoes in sub-Saharan Africa all prefer to feed close to ground level [42]. Even sitting with one's feet raised off the ground reduces mosquito biting by 32% (95% CI = 9-48%) compared with sitting with the feet planted on the floor [43]. Similar conclusions have been reached from studies conducted in Papua New Guinea which demonstrated that raised platforms were protective [44]. We have little information on the house-entering habits of *Ae. aegypti*, but it is often quoted that *Ae. aegypti* can be found in the top storeys of high-rise flats. Presumably, in these cases, adult mosquitoes fly up the stairs to higher floors, where small populations become established living in water storage containers, air conditioning units or other types of domestic water. In conclusion, there is strong evidence that raising a house off the ground will reduce mosquito house entry, and even closing the area beneath the building with permeable or impermeable walls is likely to be protective [45]. Homes are commonly raised across much of South-East Asia today [46], and we similarly recommend this for African housing, especially rural housing which is currently built at ground level.

INSECTICIDE-TREATED BEDNETS

ITNs have had a major impact in reducing malaria transmission and are considered a key tool for malaria control. Since the turn of the century, there has been massive deployment of ITNs across sub-Saharan Africa and between 2000 and 2015 the malaria infection prevalence halved and the incidence of clinical episodes of malaria declined by 40% in Africa [3]. ITNs were by far the most important malaria control intervention, and are thought to account for 62% of cases averted. A recent systematic review and meta-analysis of 23 intervention trials, enrolling more than 275,000 adults and children showed that ITNs were associated with a 42% reduction (95% CI = 22-56%) in malaria compared with untreated nets [47]. Despite the concern about increasing resistance of malaria mosquitoes to the insecticides used to treat bednets [48], the lack of durability and coverage of the nets, it is clear that ITNs are still effective weapons against malaria in sub-Saharan Africa and remain the mainstay malaria prevention tool. Surprisingly, since *Ae. aegypti* is predominantly a day-time feeder, ITNs can also be an effective tool against this mosquito as evidenced by a study in Haiti that showed this intervention caused an immediate reduction in mosquitoes after deployment [49], presumably because they contact the treated netting when flying indoors. ITN use should be strongly encouraged for malaria control in sub-Saharan Africa, but their use for the control of *Aedes*-transmitted diseases is uncertain.

VENTILATION (AND SCREENING)

One of the biggest problems facing traditional houses in sub-Saharan Africa is that they are too hot [46]. Houses constructed mud or cement blocks will heat up during the day and radiate heat at night, making the houses hot and stuffy at night. A hot bedroom at night is not conducive for sleeping under a bednet, and is the primary reason that people will not use a net at night [50]. Thus, providing ventilation to cool the building at night should help increase bednet use and hence increase protection against malaria. Improved ventilation is also important for reducing indoor air pollution, thereby reducing respiratory illness [51]. A house can be cooled by raising the building above the ground, using permeable materials for the walls of the house and, most importantly introducing large-screened windows on opposite sides of the house (Figure 3), or at least on different sides. Cross ventilation is also improved if there are no internal walls or other obstructions between the windows.

Figure 3

Unfortunately open windows need to be screened from mosquitoes, and this will typically halve the airflow across the room [52] and reduce it further if curtains are used. To maximise airflow, both windows and doors should be large, with screening to restrict mosquito-house entry. Screening is common in some African cities, such as Dar es Salaam in Tanzania, where 83% of homes surveyed had screened windows and 49% had ceilings in 2007 [53]. In Dar es Salaam a rise in mosquito screening among local residents was associated with fewer *An. arabiensis* and *An. funestus* and less malaria [54]. Interestingly, in this study the increase in screening was through commercial channels, without health promotion or subsidies. In Ethiopia, screening doors and windows reduced numbers of *An. arabiensis* indoors by 48% and malaria episodes by 61% (95% CI = 20-80%) [55]. Well-screened houses can offer additional benefits especially if there are many people sharing a bednet or where there are no bednets. Screening is an equitable intervention since it protects everyone in the house.

A high prevalence of untreated house screening, however, may, like topical repellents, increase the risk of mosquito bites in neighbouring unscreened houses [56]. It is therefore important for coverage of screening to be as high as possible. Additionally, adding insecticide to the screens could improve protection in screened houses and any unscreened neighbouring houses by reducing mosquito survival. In Vietnam, a study of insecticide-treated screening reduced both the numbers of *Ae. aegypti*, and, most importantly, provided 81% protection against dengue (95% CI = 53-92%) [57]. In Mexico, insecticide-treated screening resulted in 60% (95 CI = 30-77%) fewer *Ae. aegypti* 12 months after deployment than areas without the intervention [58], and protection lasted up to two years [58-60]. Novel forms of three-dimensional untreated screening could also serve as mosquito traps, thereby reducing both house entry and the overall mosquito population size [61]. Keeping a house well ventilated and screened would help keep houses cool at night and mosquito free.

ENVIRONMENTAL MANAGEMENT

Malaria and *Aedes*-transmitted diseases are consequences of poor water management, since without water there would be no mosquitoes. Drainage and filling are effective for reducing the aquatic habitats of *An. gambiae*, and are particularly important in urban settings [62]. In many situations, human-created habitats such as drains, concrete pits used as water sources for mixing concrete and road construction create water pooling and should be dealt with. In Khartoum, environmental management was the principal method for reducing malaria in the city [63], and was the backbone of malaria control in the Copper Belt in Zambia [64]. Although bush clearance around homes is unlikely to reduce malaria mosquito abundance [65], it can certainly help improve ventilation.

For *Ae. aegypti* the peri-domestic environment is of primary importance as a source of aquatic habitats. A plethora of small containers become a potential habitat for the immature stages of this mosquito: including discarded plastic waste, old tyres, blocked guttering, water-storage containers, [66] and underground cisterns [67]. Accumulating solid waste is a common sight in many African towns and cities. In the Nigeria delta region, only 20% of the 40,000 metric tons of waste produced daily is collected [68]. After rainfall, much of this discarded waste provides a rich source of aquatic habitats for *Ae. aegypti*. Of more immediate importance is the issue of providing water to rapidly growing cities, particularly with climate change increasing water scarcity in some places [69]. In 2018, Cape Town, home to some 4 million people, was close to fully depleting its water source, whilst in 2019, Chennai, India's sixth largest city with 4.6 million people, suffered severe water shortages. In Chennai tap water stopped running, so people collected water in containers, providing an abundance of new mosquito habitats. In such situations, water-storage containers should be covered and scrubbed weekly to remove any mosquito eggs [70]. In the long-term, cities need to plan for adequate and reliable piped water at affordable prices to reduce the potential for *Ae. aegypti* [71, 72], and other mosquito species, such as *Anopheles stephensi*. The introduction of *An. stephensi* into sub-Saharan Africa is a new and major concern since it is an important transmitter of urban malaria in India and, like *Ae. aegypti*, is also a container-breeder. Worryingly, it has recently invaded parts of northern Africa and has been identified in Djibouti, Ethiopia and Sudan [73]. If not controlled, is likely to spread to other towns and cities in the Horn of Africa. Environmental management and effective surveillance for the control of malaria and *Aedes*-transmitted diseases should be the foundation for disease control, particularly in towns and cities. Moreover, efficient solid waste management and a reliable supply of piped water is desirable for all communities and will have multiple benefits beyond mosquito control.

ROOFS

Traditional thatched-roofs, once common in much of rural Africa, are now on the decline, being replaced gradually by roofs made from solid materials, such as metal or tile [16]. For example, in Tororo district, eastern Uganda, the prevalence of thatched roofed homes decreased from 40% in 2013 to 23% in 2016 [74]. In 2011 in Rwanda, as part of a Government run programme, thatched-roofed houses were replaced with metal-roofed houses. This programme, however, has been criticised since it was alleged that force was used to remove the thatch from houses (https://www.survivalinternational.org/news/7154).

Roof types are important for malaria transmission for several reasons. First, roofs made out of solid materials such as metal may reduce opportunities for malaria mosquitoes to enter houses and provide fewer resting habitats for mosquitoes, compared to materials such as thatch [75]. Second, metal-roofed houses are hotter than traditional thatched-roofed houses, particularly when the eaves are closed [23]. This heating effect has potentially both positive and negative impacts on health. The benefit is that in hot parts of sub-Saharan Africa, the extremely high temperatures created by metal roofs and high thermal mass walls during the late afternoon are often lethal to mosquitoes sheltering indoors during the day. The high temperatures may reduce the survival of malaria mosquitoes to such an extent that few survive long enough to become infective with malaria parasites [76]. The disadvantages also results from the heating effect of metal roofs. In hot countries, the high indoor temperatures experienced during the day may be too uncomfortable for many people, who will stay outdoors, potentially exposing them to *Aedes* bites. Night-time temperatures are also hotter in metal-roofed houses, unless ventilated, than traditional thatched houses [23] and this is likely to increase the time spent by people outside the house, reduce the number of people sleeping under a bednet at night [50] , and may even contribute to increased growth faltering in young children living in hot houses [77].

Evidence from a systematic review of observational studies suggests that modern roof materials such as metal are associated with reductions in the incidence of clinical malaria, compared to traditional materials such as thatch [17]. For example, an observational study in Burkina Faso found that children living in mud-roofed houses were nearly three times at greater risk of malaria infection than those living in metal-roofed houses [78]. However, caution is needed in interpreting the findings from observational studies since protection may not be related to the presence of a metal roof, but to the presence of closed eaves or confounded by socioeconomic status. In these correlational studies a metal roof, or more simply, a good home, may be a marker for a higher socioeconomic status, and other features of being wealthy may be protective, such as the ability to purchase antimalarials or own and use a bednet. Even adjusting for socioeconomic status in a risk model, one cannot exclude the possibility of residual confounding - that good housing is a measure of wealth. Despite these caveats, cheap, durable and clean alternatives to thatch roofs, as well as the incorporation of ceilings or screening below different roof materials should be explored in sub-Saharan Africa to reduce disease transmission, provided the house can remain well ventilated to keep the interior cool. Further research is needed to identify the best solid roof types and combinations of roof materials, solid ceilings and ceiling screening for disease control.

Facilitators

The recommendations comprising the DELIVER mnemonic are intended to be implemented as an integrated package addressing multiple hazards in the transition to healthier homes. Nonetheless, certain recommendations may be more appropriate depending on each particular situation. To roll-out such innovations, important enablers or 'facilitators' are needed.

(a) Political leadership

Reducing the risk of mosquito-transmitted diseases by changes to the built environment on a large scale requires that we do things differently; this is not something the health sector can do alone. Multi-sectoral action against mosquito-transmitted diseases is needed to control diseases more sustainably and at a lower cost than traditional mosquito-control interventions and necessitates the health sector working with those in the built environment; including those responsible for housing, infrastructure, parks, waste management and water (Figure 4). One framework to do this is through established committees developing resilience plans for towns and cities. This is an opportunity for the United Nations Housing Unit to engage with these messages to contribute to international guidelines of producing healthy houses and communities for the future. Thus where resilience activities are being planned for the future, this may be the most appropriate institutional structure for developing action plans. Where this is not established, multir-sectoral committees need to be formed. Success relies on strong leadership, effective governance structures, political commitment and the necessary financial resources to make the changes. Countries wanting to tackle so called 'wicked' problems such as obesity or mosquito-transmitted diseases are increasingly adopting a whole-of-government approach, whereby public institutions work across portfolio boundaries to achieve a shared goal [79, 80]. Two recent examples of success come from Khartoum city in Sudan [63] and Singapore [81]. City mayors are in a powerful position to take multi-sectoral action against mosquito-transmitted diseases by forging links between sectors and, most importantly, providing the financial support needed.

Figure 4

(b) Private sector involvement

Engagement of the private sector can help reduce mosquito habitats in the environment. For example, in Brazil a public-private partnership between the Ministry of Environment and Reciclanip (http://www.reciclanip.org.br/), an organisation linked to the National Association of the Tyre Industry, collected and recycles scrap tyres that provide an ideal habitat for *Aedes* mosquitoes. Tyres are recycled into a range of useful materials including flooring for sports facilities, added to asphalt or used as an alternative fuel in the cement industry replacing fossil fuels. The partnership is a win-win since the recycling industry boosts the economy by employing large numbers of people. In Lagos, recyclable waste is collected using a fleet of cargo bikes, motorized tricycles, vans and trucks (http://wecyclers.com/about). The collected material is exchanged for food and household items and then converted to tissue paper, stuffing for mattresses, plastic furniture, aluminium sheets and nylon bags. Such innovative solutions offer exciting ways for removing waste, reducing mosquito habitats and creating a new industry.

(c) Community participation

Extensive changes to the built environment can only be successful with the partnership of local communities. Thus the possibilities for change ideally should come from the grassroots, and when not need to be discussed with local residents and decisions made with their support to ensure maximum effectiveness and sustainability of any solutions. A good example of such a process was the Camino Verde (Green way) campaign in Nicaragua and Mexico [82]. Here insecticide-free interventions (emptying, brushing/scrubbing water containers or covering them) identified and mediated through community mobilisation reduced the abundance of *Ae. aegypti* and increased the effectiveness of government programmes to control dengue. Similarly, effective community-led interventions have been successful in Cuba [83], Indonesia [84], Kenya [85], Mexico [86] and Puerto Rico [87].

The DELIVER recommendations can be implemented whilst preserving vernacular building styles and skills – rather than promoting a homogenous house structure across all cultures and geographies. It is important, therefore, that community participation should include local architecture, engineering and design schools [87].

(d) Education

In East Africa, city engineers were once imbedded into malaria control programmes, to help remove surface water through drainage and filling [88]. Today, this no longer happens, and few engineers are taught about the critical importance of public health engineering and politicians have failed to emphasise the importance of public health considerations in construction and urban planning. Architects and city planners do not always take into considerations the implications their designs and projects have on health, they have not developed a holistic vision of spaces. This needs to change, and in disease-endemic countries teaching about diseases caused by mosquitoes and methods for their control needs to be incorporated into curricula from primary, secondary to tertiary training bodies, especially those dealing with the built environment. Additionally, within the education system there should be an emphasis on the intersectionality of these challenges, the need for multi-sectoral solutions to target them. With education comes innovation and the creation of new methods for controlling these diseases. The use of social media offers exciting opportunities for spreading knowledge and good practice. Healthy, 'Show homes' are also a novel way to share good practice, as illustrated by entirely new 'healthy' house designs in the Magoda project carried out in Tanzania [52].

Global policy supporting 'building out' mosquito-transmitted diseases

Malaria and *Aedes*-transmitted diseases are environmental diseases: the risk of each is influenced by local environmental factors. Over recent years there has been a growing appreciation that action to improve people's health needs to also to take action against the social and environmental determinants of health [89, 90]. Such an approach recognises that health can no longer be the sole responsibility of the health sector and calls for greater cross-sectoral collaboration, particularly at the local level such as local authorities. Changing global policy provides a key opportunity for acknowledging and addressing such challenges.

The United Nations' Sustainable Development Goals (SDGs) explicitly acknowledges the importance of cross-sectoral collaboration since all the goals are inter-connected. The SDGs most closely linked to addressing mosquito-transmitted diseases are Goal 3: Good Health and Well-being, Goal 11: Sustainable Cities and Communities and Goal 17: Partnerships to achieve the Goals.

For health professionals specifically, The United Nations Development Programme (UNDP) and the Roll Back Malaria Partnership (RBM) published key documents on the importance of multi-sectoral action for malaria control [91] and later RBM, UNDP and UN-Habitat produced the first policy document supporting housing interventions for malaria control, called the housing and malaria consensus statement [92]. Importantly, WHO's strategy for the control of mosquito-transmitted diseases, the Global Vector Control Response 2017-30 [2], strongly advocates the need for multi-sectoral action, especially in respect to malaria and *Aedes*-transmitted diseases.

For built environment professionals, the United Nations' New Urban Agenda (NUA) [93], provides global guidelines for achieving sustainable urban development. The NUA explicitly recognises urban centres as exhibiting characteristics that make them and their inhabitants particularly vulnerable to climate change and other natural and human-made hazards, including mosquito-transmitted diseases (like malaria and *Aedes*-transmitted diseases) [94, 95]. The NUA speaks particularly to local authorities. Many national governments' attempts to implement multi-sectoral policy fail on account of the inability to embrace the concept at local authority level. There are many opportunities through for example local bylaws etc. to promote multi-sectoral approaches and to influence the design specifications for housing and promote environmental management approaches.

More specifically, for actors working on improving the disaster resilience of cities to support sustainable urban development there is the United Nations Office for Disaster Risk Reduction's (UNDRR, formerly UNISDR) Sendai Framework for Disaster Risk Reduction 2015-2030 [96]. The framework more directly relates to the built environment through the 'Ten Essentials for Making Cities Resilient' operating framework delivered through UNDRR's 'Making Cities Resilient' campaign (unisdr.org/campaign/resilientcities). While it does refer to health as a key element, there is no reference to mosquito-transmitted diseases in the Sendai framework and by extension the essentials or campaign. This is a missed opportunity, since malaria and *Aedes*-transmitted diseases are an engineering problem, not just a health problem.

Another key opportunity relates to the WHO Housing and health guidelines (HHGL)[97] that were published in December 2018. The HHGL provide practical recommendations to reduce the health burden due to unsafe and substandard housing conditions in order to inform housing policies and regulations at the national, regional and local level. Unfortunately, the first edition of the HHGL does not cover housing interventions that protect from vector-borne diseases. However, it is the intention of WHO to rectify this omission in the next edition.

Conclusion

DELIVER describes the packet of interventions that when used together will be effective in the fight against mosquito-transmitted diseases. The selection of interventions is based on the best evidence we have to date, but new evidence may bring improvements and/or modifications and new technologies are continually emerging. It is important that such innovations are rigorously assessed before including them in our current arsenal of interventions [98]. It is also vital that further research is conducted on the ecology and behaviour of *Ae. aegypti* in the domestic environment, so that we can design better interventions against this formidable foe. DELIVER will contribute positively to several SDG goals, including goal 3 (Good health and well-being), goal 6 (clean water and sanitation), goal 9 (industry, innovation and infrastructure), goal 11 (sustainable cities and communities), goal 13 (climate action) and goal 17 (partnerships to achieve the goal) whilst reducing the amount of insecticides used.

Many of the suggestions made in this manuscript are not specifically directed at solely shrinking the number of cases of mosquito-transmitted diseases. For example, providing reliable piped water, effective waste management and drainage and having a quiet night's sleep undisturbed from biting mosquitoes is something very few of us reading this article would disagree with: it is development. But, the considerable threat from mosquito-transmitted diseases provides us with an impetus to direct our efforts at those areas most in need and provides an urgency for action. We also acknowledge that improvements in housing are also likely to lead to other improvements in health, including reduced incidence of diarrhoea, anaemia and undernutrition [99]. Such changes will also provide many collateral benefits including reducing the use of insecticides, reducing the threat of flooding and helping to reduce plastic waste in our communities. Control of mosquito-transmitted diseases has the potential to be more sustainable than other typical vector control interventions, particularly if the community and other stakeholders are engaged in the design and implementation of solutions. Building resilience against mosquito-transmitted diseases is very much part of a green revolution, providing safe and resilient communities for the future. Importantly we need to build out mosquito-transmitted diseases from our communities, not build them in.

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References

1. Golding N, Moyes CL, Wilson AL, Cano J, Pigott DM, Velayudhan R, Brooker SJ, Smith DL, Hay SI, Lindsay SW. 2015 Integrating vector control across diseases. *BMC Medicine* **13**. (doi:10.1186/s12916-015-0491-4).
2. WHO. 2017 Global Vector Control Response 2017-2030. Geneva, WHO.
3. Bhatt S, Weiss DJ, Cameron E, Bisanzio D, Mappin B, Dalrymple U, Battle K, Moyes CL, Henry A, Eckhoff PA, et al. 2015 The effect of malaria control on *Plasmodium falciparum* in Africa between 2000 and 2015. *Nature* **526**, 207-211. (doi:10.1038/nature15535).
4. WHO. 2019 *World Malaria Report 2019*. Geneva, WHO.
5. Tusting LS, Bisanzio D, Alabaster G, Cameron E, Cibulskis R, Davies M, Flaxman S, Gibson H, Knudsen J, Mbogo C, Okumu, FO, Rust K, von Seidlein L, Weiss D, Lindsay SW, Gething PW, Bhatt S. 2020 Mapping changes in housing in Africa, 2000 to 2015 *Nature* **568**, 391-394. (doi:10.1038/s41586-019-1050-5).
6. Weetman D, Kamgang B, Badolo A, Moyes CL, Shearer FM, Coulibaly M, Pinto J, Lambrechts L, McCall PJ. 2018 *Aedes* mosquitoes and *Aedes*-borne arboviruses in Africa: current and future threats. *Int. J. Environ. Res. Publ. Hlth* **15**, e220. (doi:10.3390/ijerph15020220).

7. Stanaway JD, Shepard DS, Undurraga EA, Halasa YA, Coffeng LE, Brady OJ, Hay SI, Bedi N, Bensenor IM, Castaneda-Orjuela CA, et al. 2016 The global burden of dengue: an analysis from the Global Burden of Disease Study 2013. *Lancet Infect Dis* **16**, 712-723. (doi:10.1016/S1473-3099(16)00026-8).
8. WHO. 2019 Key facts: dengue and severe dengue. (Geneva, WHO.
9. Amarasinghe A, Kuritsk JN, Letson GW, Margolis HS. 2011 Dengue virus infection in Africa. *Emerg Infect Dis* **17**, 1349-1354. (doi:10.3201/eid1708.101515).
10. WHO. 2016 Situation report. Yellow fever. 28 October 2016 (Geneva World Health Organization.
11. Mulchandani R, Massebo F, Bocho F, Jeffries CL, Walker T,Messenger LA. 2019 A community-level investigation following a yellow fever virus outbreak in South Omo Zone, South-West Ethiopia. *Peerj* **7**, e6466. (doi:10.7717/peerj.6466).
12. WHO. 2018 Zika Virus (ZIKV) classification table. Data as of 15 February 2018. Geneva, WHO.
13. WHO. 2019 Chikungunya - Congo. DIsease outbreak news, 1 May 2019. Geneva, WHO.
14. UNDESAPD. 2019 2019 revisions of world population prospects. New York, United Nations, Department of Economic and Social Affairs, Population Division.
15. Institute MG. 2016 Lions on the move II: realizing the potential of Africa's economies. Brussels, McKinsey & Co.
16. Tusting L, Bisanzio D, Alabaster G, Cameron E, Cibulskis R, Davies M, Flaxman S, Gibson H, Knudsen J, Mbogo C, et al. 2020 Mapping changes in housing in sub-Saharan Africa from 2000 to 2015. *Nature*. 568, 391-394 (doi:10.1038/s41586-019-1050-5).
17. Tusting LS, Ippolito MM, Willey BA, Kleinschmidt I, Dorsey G, Gosling R, Lindsay SW. 2015 The evidence for improving housing to reduce malaria: a systematic review and meta-analysis *Malaria J* **14**, e209. (doi:10.1186/s12936-015-0724-1).
18. Tusting LS, Bottomley C, Gibson H, Kleinschmidt I, Tatem AJ, Lindsay SW, Gething PW. 2017 Housing improvements and malaria risk in Sub-Saharan Africa: a multi-country analysis of survey data. *PLoS Med.* **14**, e1002234. (doi:10.1371/journal.pmed.1002234).
19. Huho B, Briet O, Seyoum A, Sikaala C, Bayoh N, Gimnig J, Okumu F, Diallo D, Abdulla S, Smith T, et al. 2013 Consistently high estimates for the proportion of human exposure to malaria vector populations occurring indoors in rural Africa. *Int. J. Epidemiol.* **42**, 235-247. (doi:Doi 10.1093/Ije/Dys214).
20. Sherrard-Smith E, Skarp JE, Beale AD, Fornadel C, Norris LC, Moore SJ, Mihreteab S, Charlwood JD, Bhatt S, Winskill P, et al. 2019 Mosquito feeding behavior and how it influences residual malaria transmission across Africa. *Proc. Natl. Acad. Sci. USA.* **116**, 15086-15095. (doi:10.1073/pnas.1820646116).
21. Gillies MT. 1980 The role of carbon dioxide in host finding by mosquitoes (Diptera: Culicidae): a review. *Bul. Entomol. Res.* **70**, 525-532. (doi:/10.1017/S0007485300007811).
22. Kirby MJ, Green C, Milligan PM, Sismanidis C, Jasseh M, Conway DJ, Lindsay SW. 2008 Risk factors for house-entry by malaria vectors in a rural town and satellite villages in The Gambia. *Malaria J* **7**, e2. (doi:10.1186/1475-2875-7-2).
23. Jatta E, Jawara M, Bradley J, Jeffries D, Kandeh B, Knudsen JK, Wilson AL, Pinder M, D'Alessandro U, Lindsay SW. 2018 How house design affects malaria mosquito density, temperature, and relative humidity: an experimental study in The Gambia. *Lancet Planet. Hlth.* **2** e498-508. (doi:10.1016/S2542-5196(18)30234-1.).
24. Jatta E. 2018 The impact of different house designs on mosquito house entry in rural Gambia. PhD thesis, Durham, Durham University.
25. Snow WF. 1987 Studies of the house-entering habits of mosquitoes in The Gambia, West Africa: experiments with prefabricated huts with varied wall apertures. *Med. Vet. Entomol.* **1**, 9-21. (doi:10.1111/j.1365-2915.1987.tb00318.x).
26. WHO. 1982 *Manual on environmental management for mosquito control, with special emphasis on malaria vectors. WHO Offset Publication No. 66*. Geneva, World Health Organisation.
27. Rozendaal JA. 1997 *Vector Control: methods for use by individuals and communities* Geneva, World Health Organization.

28. Authority TV. 1947 *Malaria control on impounded waters.* Washington DC, United States Public Health Service.
29. Kirby MJ, Ameh D, Bottomley C, Green C, Jawara M, Milligan PJ, Snell PC, Conway DJ, Lindsay SW. 2009 Effect of two different house screening interventions on exposure to malaria vectors and on anaemia in children in The Gambia: a randomised controlled trial. *Lance.t* **374**, 998-1009. (doi:10.1016/S0140-6736(09)60871-0).
30. Jawara M, Jatta E, Bell D, Burkot TR, Bradley J, Hunt V, Kandeh B, Jones C, Manjang AM, Pinder M, et al. 2018 New prototype screened doors and windows for excluding mosquitoes from houses: a pilot study in rural Gambia. *Am. J. Trop. Med. Hyg.* **99**, 1475-1484. (doi:10.4269/ajtmh.18-0660.).
31. Lindsay SW Snow RW. 1988 The trouble with eaves; house entry by vectors of malaria. *Trans. Roy. Soc. Trop. Med. Hyg.* **82**, 645-646. (doi:10.1016/0035-9203(88)90546-9).
32. Wanzirah H, Tusting, LS, Arinaitwe E, Katureebe A, Maxwell K, Rek J, Bottomley C, Staedke SG, Kamya M, Dorsey G, Lindsay SW. 2015 Mind the gap: house structure and the risk of malaria in Uganda. *PLoS ONE.* **10** e0117396. (doi: 10.1371/journal.pone.0117396).
33. Lindsay SW, Emerson PM, Charlwood JD. 2002 Reducing malaria by mosquito-proofing houses. *Trends Parasitol.* **18**, 510-514. (doi:10.1016/s1471-4922(02)02382-6).
34. Ogoma SB, Lweitoijera DW, Ngonyani H, Furer B, Russell TL, Mukabana WR, Killeen GF, Moore SJ. 2010 Screening mosquito house entry points as a potential method for integrated control of endophagic filariasis, arbovirus and malaria vectors. *PLoS Neglect. Trop. Dis.* **4**, 8 (doi:10.1371/journal.pntd.0000773).
35. Lindsay SW, Jawara M, Paine K, Pinder M, Walraven GE, Emerson PM. 2003 Changes in house design reduce exposure to malaria mosquitoes. *Trop. Med. Int. Health.* **8**, 512-517. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=12791056
36. Herodotus Sélincourt Ad. 1996 *Herodotus. The histories*. London, Penguin; 622.
37. Celli A. 1900 Notes on the new researches on the propagation of malaria in relation to engineering and agriculture. *J. Sanit. Inst.* **21**, 617-628.
38. Snow WF. 1975 The vertical distribution of flying mosquitoes (Diptera, Culicidae) in West African savanna. *Bull. Entomol. Res.* **65**, 269-277. (doi:10.1017/S0007485300005952).
39. Snow WF. 1979 The vertical distribution of flying mosquitoes (Diptera: Culicidae) near an area of irrigated rice-fields in The Gambia. *Bull. Entomol. Re.s* **69**, 561-571. (doi:10.1017/S0007485300020113).
40. Gillies MT, Wilkes TJ. 1976 The vertical distribution of some West African mosquitoes (Diptera, Culicidae) over open farmland in a freshwater area of The Gambia. *Bull. Entomol. Res.* **66**, 5-15. (doi:10.1017/S0007485300006441).
41. Gillies MT, Wilkes TJ. 1978 The effect of high fences on the dispersal of some West African mosquitoes (Diptera: Culicidae). *Bull. Entomol. Res.* **68**, 401-408. (doi:10.1017/S0007485300006441).
42. Braack L, Hunt R, Koekemoer LL, Gericke A, Munhenga G, Haddow AD, Becker P, Okia M, Kimera I, Coetzee M. 2015 Biting behaviour of African malaria vectors: 1. where do the main vector species bite on the human body? *Parasit. Vect.* **8**, e76 (doi:10.1186/s13071-015-0677-9).
43. Lindsay SW, Janneh LM. 1989 Preliminary field trials of personal protection against mosquitoes in the gambia using deet or permethrin in soap, compared with other methods. *Med. Vet. Entomol.* **3**, 97-100. (doi:10.1111/j.1365-2915.1989.tb00481.x).
44. Charlwood JD, Paru R, Dagoro H. 1984 Raised platforms reduce mosquito bites. *Trans. Roy. Soc. Trop. Med. Hyg.* **78**, 141-142. (doi:10.1016/0035-9203(84)90204-9).
45. von Seidlein L, Ikonomidis K, Mshamu S, Nkya TE, Mukaka M, Pell C, Lindsay SW, Deen JL, Kisinza WN, Knudsen JB. 2017 Affordable house designs to improve health in rural Africa: a field study from northeastern Tanzania. *Lancet Planet. Hlth.* **1**, e188-e199. (doi:10.1016/S2542-5196(17)30078-5).
46. Knudsen J Von Seidlein L. 2014 *Healthy homes in tropical zones: improving rural housing in Asia and Africa* Stuttgart/London, Axel Menges.

47. Pryce J, Richardson M, Lengeler C. 2018 Insecticide-treated nets for preventing malaria. *Cochrane Database Syst. Rev.* **11**, CD000363. (doi:10.1002/14651858.CD000363.pub3.).
48. Ranson H, Lissenden N. 2016 Insecticide resistance in African *Anopheles* mosquitoes: a worsening situation that needs urgent action to maintain malaria control. *Trends Parasitol.* **32**, 187-196. (doi:10.1016/j.pt.2015.11.010).
49. Lenhart A, Orelus N, Maskill R, Alexander N, Streit T, McCall PJ. 2008 Insecticide-treated bednets to control dengue vectors: preliminary evidence from a controlled trial in Haiti. *Trop. Med. Int. Hlth.* **13**, 56-67. (doi:10.1111/j.1365-3156.2007.01966.x).
50. Pulford J, Hetzel MW, Bryant M, Siba PM, Mueller I. 2011 Reported reasons for not using a mosquito net when one is available: a review of the published literature. *Malaria J.* **10**, 83. (doi:10.1186/1475-2875-10-83).
51. Buchner H, Rehfuess EA. 2015 Cooking and season as risk factors for acute lower respiratory infections in African children: a cross-sectional multi-country analysis. *PLoS One*. **10**, 6. (doi:10.1371/journal.pone.0128933).

52. von Seidlein L, Ikonomidis K, Mshamu S, Nkya TE, Mukaka M, Pell C, Lindsay SW, Deen JL, Kisinza WN, Knudsen JB. 2017 Affordable house designs to improve health in rural Africa: a field study from northeastern Tanzania. *Lancet Planet. Hlth.* **1**, e188-199. (doi:10.1016/S2542-5196(17)30078-5).
53. Ogoma SB, Kannady K, Sikulu M, Chaki PP, Govella NJ, Mukabana WR,Killeen GF. 2009 Window screening, ceilings and closed eaves as sustainable ways to control malaria in Dar es Salaam, Tanzania. *Malaria J*. **8**, 1. (doi:10.1186/1475-2875-8-221).
54. Killeen GF, Govella NJ, Mlacha YP, Chaki PP. 2019 Suppression of malaria vector densities and human infection prevalence associated with scale-up of mosquito-proofed housing in Dar es Salaam, Tanzania: re-analysis of an observational series of parasitological and entomological surveys. *Lancet Plane.t Hlth.* **3**, e132-e143. (doi:10.1016/S2542-5196(19)30035-X).
55. Getawen SK, Ashine T, Massebo F, Woldeyes D, Lindtjorn B. 2018 Exploring the impact of house screening intervention on entomological indices and incidence of malaria in Arba Minch town, southwest Ethiopia: a randomized control trial. *Acta Trop.* **181**, 84-94. (doi:10.1016/j.actatropica.2018.02.009).
56. Maia M, Sangoro P, Thele M, Turner E, Moore S. 2012 Do topical repellents divert mosquitoes within a community? *Malaria J*. **11**, S67-S68. (doi:10.1371/journal.pone.0084875).
57. Nguyen HT, Tien TV, Tien NC, Tinh TU, Hoa NT. 1996 The effect of Olyset net screen to control the vector of dengue fever in Viet Nam. *Dengue Bull.* **20**, 87–92. (doi:https://apps.who.int/iris/handle/10665/147874).
58. Manrique-Saide P, Che-Mendoza A, Barrera-Perez M, Guillermo-May G, Herrera-Bojorquez J, Dzul-Manzanilla F, Gutierrez-Castro C, Lenhart A, Vazquez-Prokopec G, Sommerfeld J, et al. 2015 Use of insecticide-treated house screens to reduce infestations of dengue virus vectors, Mexico. *Emer.g Infect. Dis.* **21**, 308-311. (doi:10.3201/eid2102.140533).
59. Che-Mendoza A, Guillermo-May G, Herrera-Bojorquez J, Barrera-Perez M, Dzul-Manzanilla F, Gutierrez-Castro C, Arredondo-Jimenez JI, Sanchez-Tejeda G, Vazquez-Prokopec G, Ranson H, et al. 2015 Long-lasting insecticide-treated house screens and targeted treatment of productive breeding-sites for dengue vector control in Acapulco, Mexico. *Trans. Roy. Soc. Trop. Med. Hyg.* **109**, 106-115. (doi:10.1093/trstmh/tru189).
60. Che-Mendoza A, Medina-Barreiro A, Koyoc-Cardena E, Uc-Puc V, Contreras-Perera Y, Herrera-Bojorquez J, Dzul-Manzanilla F, Correa-Morales F, Ranson H, Lenhart A, et al. 2018 House screening with insecticide-treated netting provides sustained reductions in domestic populations of *Aedes aegypti* in Merida, Mexico. *Plos Neglect Trop D* **12**. (doi:10.1371/journal.pntd.0006283).

61. Khattab A, Jylha K, Hakala T, Aalto M, Malima R, Kisinza W, Honkala M, Nousiainen P,Meri S. 2017 3D mosquito screens to create window double screen traps for mosquito control. *Parasit. Vector.* **10**. (doi:10.1186/s13071-017-2322-2).

62. Castro MC, Kanamori S, Kannady K, Mkude S, Killeen GF, Fillinger U, De Castro MC, Kanamori S, Kannady K, Mkude S, et al. 2010 The importance of drains for the larval development of lymphatic filariasis and malaria vectors in Dar es Salaam, United Republic of Tanzania. *PLoS Neglect. Trop. Dis.* **4**, e693 (doi:e693 10.1371/journal.pntd.0000693).
63. WHO. 2016 *A toolkit for integrated vector management in sub-Saharan Africa*. Geneva, WHO.
64. Watson M. 1953 *African highway: the battle for health in Central Africa.* London, John Murray.
65. Opiyo P, Mukabana WR, Kiche I, Mathenge E, Killeen GF,Fillinger U. 2007 An exploratory study of community factors relevant for participatory malaria control on Rusinga Island, western Kenya. *Malaria J.* **6**, 48. (doi:10.1186/1475-2875-6-48).
66. Lindsay SW, Wilson A, Golding N, Scott TW,Takken W. 2017 Improving the built environment in urban areas to control *Aedes aegypti*-borne diseases *Bull. WHO.* **95**, 607-608 (doi: 10.2471/BLT.16.189688).
67. WHO. 2020 Managing the links between water storage and dengue vectors in Barbados. (Geneva, WHO.
68. Numbere AO. 2019 Municipal solid waste disposal in mangrove forest: environmental implication and management strategies in the Niger Delta, Nigeria. In *Municipal Solid Waste Management* (ed. HE Saleh). Cairo, Egypt, Egyptian Atomic Energy Authority.
69. Padmanabha H, Soto E, Mosquera M, Lord CC, Lounibos LP. 2010 Ecological links between water storage behaviors and *Aedes aegypti* production: implications for dengue vector control in variable climates. *Ecohealth* **7**, 78-90. (doi:10.1007/s10393-010-0301-6).
70. Phuanukoonnon S, Mueller I,Bryan JH. 2005 Effectiveness of dengue control practices in household water containers in Northeast Thailand. *Trop. Med. Int. Hlth,* **10**, 755-763. <Go to ISI>://WOS:000230727500007.
71. Tsuzuki A, Huynh T, Luu L, Tsunoda T,Takagi M. 2009 Effect of water supply system installation on distribution of water storage containers and abundance of *Aedes aegypti* immatures in urban premises of Ho Chi Minh City, Viet Nam. *Dengue Bull.* **33**, 161-166. (doi:https://apps.who.int/iris/handle/10665/170730).
72. Schmidt WP, Suzuki M, Thiem VD, White RG, Tsuzuki A, Yoshida LM, Yanai H, Haque U, Tho LH, Anh DD, et al. 2011 Population density, water supply, and the risk of dengue fever in Vietnam: cohort study and spatial analysis. *PloS Med.* **8**, 8. (doi:10.1371/journal.pmed.1001082).
73. WHO. 2019 Vector alert: *Anopheles stephensi* invasion and spread. Geneva, WHO.
74. Rek J, Alegana V, Arinaitwe E, Cameron E, Kamya M, Katureebe A, Lindsay SW, Kilama M, Staedke SG, Todd J, et al. 2018 Rapid improvements to rural Ugandan housing and their association with malaria from intense to reduced transmission: findings from a cohort study. *Am. J. Trop. Med. Hyg.* **99**, 662-662. (doi:10.1016/S2542-5196(18)30010-X.).
75. Msugupakulya BJ, Kaindoa EW, Ngowo HS, Kihonda JM, Kahamba NF, Msaky DS, Matoke-Muhia D, Tungu PK,Okumu FO. 2020 Preferred resting surfaces of dominant malaria vectors inside different house types in rural south-eastern Tanzania. *Malaria J.* **19**, 22. (doi:10.1186/s12936-020-3108-0).
76. Lindsay SW, Jawara M, Mwesigwa J, Achan J, Bayoh N, Bradley J, Kandeh B, Kirby MJ, Knudsen J, Macdonald M, et al. 2019 Reduced mosquito survival in metal-roof houses may contribute to a decline in malaria transmission in sub-Saharan Africa. *Sci. Rep-Uk.* **9**, 7770. (doi:10.1038/s41598-019-43816-0).
77. Tusting LS, Bradley, J., Bhatt, S., Gibson, H.H., Weiss, D.J., Shenton, F.C. & Lindsay, S.W. in press Environmental temperature and growth faltering in African children: a cross-sectional study *Lancet Planet. Hlth*.
78. Ye Y, Hoshen M, Louis V, Seraphin S, Traore I,Sauerborn R. 2006 Housing conditions and *Plasmodium falciparum* infection: protective effect of iron-sheet roofed houses. *Malar J.* **5**, 8. (doi:10.1186/1475-2875-5-8).
79. Hunter DJ. 2009 Leading for health and wellbeing: the need for a new paradigm. *J. Publ. Hlth.* **31**, 202-204. <Go to ISI>://MEDLINE:19372148.
80. Colgan A, Kennedy L, Doherty N. 2014 A primer on implementing whole of government approaches. Dublin, Dublin Centre for Effective Services.

81. Sim S, Ng, L.C., Lindsay, S.W., Wilson, A. submitted A greener vision for vector control: the example of the Singapore dengue control programme *PLoS NTDs*.

82. Andersson N, Nava-Aguilera E, Arostegui J, Morales-Perez A, Suazo-Laguna H, Legorreta-Soberanis J, Hernandez-Alvarez C, Fernandez-Salas I, Paredes-Solis S, Balmaseda A, et al. 2015 Evidence based community mobilization for dengue prevention in Nicaragua and Mexico (Camino Verde, the Green Way): cluster randomized controlled trial. *Brit. Med. J.* **351**, h3267. (doi:10.1136/bmj.h3267).

83. Sanchez L, Perez D, Perez T, Sosa T, Cruz G, Kouri G, Boelaert M, Van der Stuyft P. 2005 Intersectoral coordination in *Aedes aegypt*i control. A pilot project in Havana City, Cuba. *Trop. Med. Int. Hlth.* **10**, 82-91. (doi:10.1111/j.1365-3156.2004.01347.x).

84. Suroso H Suroso T. 1990 *Aedes aegypti* control through source reduction by community efforts in Pekalongan, Indonesia. *Mosquitoborne Dis. Bull.* **7**, 59-62. (doi:https://www.cabdirect.org/cabdirect/abstract/19912078008).

85. Mutero CM, Mbogo C, Mwangangi J, Imbahale S, Kibe L, Orindi B, Girma M, Njui A, Lwande W, Affognon H, et al. 2015 An assessment of participatory integrated vector management for malaria control in Kenya. *Environ.l Hlth. Perspect.* **123**, 1145-1151. (doi:10.1289%2Fehp.1408748).

86. Barrera-Perez MA, Pavia-Ruz N, Mendoza-Mezquita JE, Torres-Arcila N, Hernandez-Hernandez R, Castro-Gamboa F, Geded-Moreno E, Cohuo-Rodriguez A, Medina-Barreiro A, Koyoc-Cardena E, et al. 2015 Control of *Aedes aegypti* breeding sites with the program Recicla por tu bienestar in Merida, Mexico. *Salud. Publ. Mexico.* **57**, 201-210. <Go to ISI>://WOS:000356026700008.

87. Winch PJ, Leontsini E, Rigau-Perez JG, Ruiz-Perez M, Clark GG,Gubler DJ. 2002 Community-based dengue prevention programs in Puerto Rico: Impact on knowledge, behavior, and residential mosquito infestation. *Am. J. Trop. Med. Hyg*. **67**, 363-370. (doi:10.4269/ajtmh.2002.67.363).

88. Wilson AL, Courtenay O, Kelly-Hope LA, Scott TW, Takken W, Torr SJ, Lindsay SW. 2020 The importance of vector control for the control and elimination of vector-borne diseases *Plos Neglect. Trop. Dis.* **14**, e0007831(doi:10.1371/journal.pntd.0007831).

89. Marmot M. Allen J. 2015 Health priorities and the social determinants of health. *East. Medit. Hlth. J.* **21**, 671-672. (doi:https://apps.who.int/iris/handle/10665/255315).

90. CSDH. 2008 Closing the gap in a generation: health equity through action on the social determinants of health. Final Report of the Commission on Social Determinants of Health. Geneva, World Health Organization.

91. RBM/UNDP. 2013 *Multisectoral action framework for malaria* Geneva, UNDP and RBM.

92. RBM/UNDP/UN-Habitat. 2015 Housing and malaria consensus statement. Geneva, RBM/UNDP?UN-Habitat.

93. UN. 2017 New Urban Agenda. Habitat III Quito 17-20 October 2016. United Nations conference on housing and sustainable urban development. New York, United Nations.

94. Li RY, Xu L, Bjornstad ON, Liu KK, Song T, Chen AF, Xu B, Liu QY, Stenseth NC. 2019 Climate-driven variation in mosquito density predicts the spatiotemporal dynamics of dengue. *Proc. Nat. Acad. Sci. USA.* **116**, 3624-3629. (doi:10.1073/pnas.1806094116).

95. IPCC. 2014 Climate change 2014. Impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Cambridge, Cambridge University Press.

96. UNISDR. 2016 fact sheet: health in the context of the Sendai framework for disaster risk reduction. Geneva, UNISDR.

97. WHO. 2018 Housing and health guidelines. Geneva, WHO.

98. Wilson AL, Boelaert M, Kleinschmidt I, Pinder M, Scott TW, Tusting LS, Lindsay SW. 2015 Evidence-based vector control? Improving the quality of vector control trials. *Trends Parasitol.* **31**, 380-390. (doi:10.1016/j.pt.2015.04.015).

99. Tusting L, Gething P, Gibson H, Greenwood B, Knudsen J, Lindsay S, Bhatt S. in press Housing and child health in sub-Saharan Africa: a cross-sectional analysis. *PLoS Medicine*.

100. Fillinger U Lindsay SW. 2011 Larval source management for malaria control in Africa: myths and reality. *Malaria J* **10**, 353-353. (doi:10.1186/1475-2875-10-353).

Box 1. Essential entomology

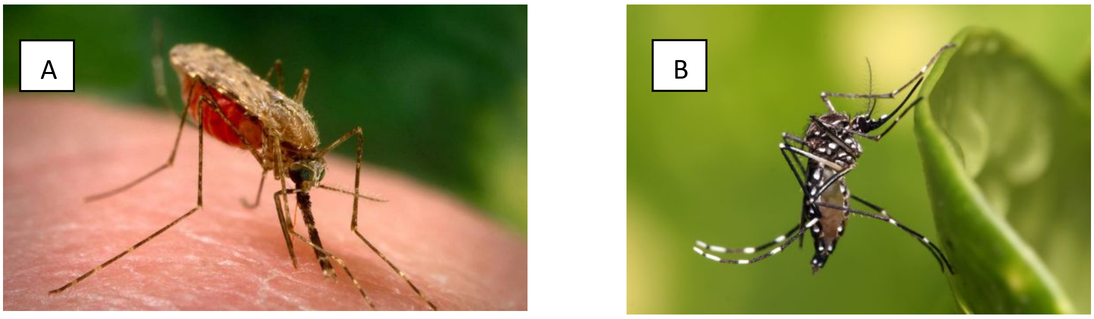


Figure: A, *Anopheles gambiae*, the main transmitter of malaria in Africa, and B, *Aedes aegypti*, the world's best transmitter of viruses including dengue, yellow fever, Zika and chikungunya.

Experts on mosquito-transmitted diseases can miss out this section, but for those new to the subject, please read on. In sub-Saharan Africa, the predominant transmitter of malaria is the mosquito *Anopheles gambiae*. It is actually a complex of species that look similar, but each has markedly different behaviours and ecology. For our purpose, there are three species that are important: *An. gambiae sensu stricto* (in the strict sense), *An. coluzzii* and *An. arabiensis*. Both *An. gambiae s.s.* and *An. coluzzii* are extraordinarily adapted for feeding on people indoors, whilst *An. arabiensis* is less choosy in its feeding preference feeding on humans and large domestic animals, and will feed indoors and outdoors. The aquatic habitats of the malaria transmitters are generally man-made and wide ranging, including small ponds, drainage ditches, rice fields and foot and tyre prints [100]. A fourth species, *An. funestus*, is also important and has a propensity for flooded denser vegetation, such as overgrown ditches. For all four mosquito species, the aquatic habitats are rural in character, but can also be found readily on the edges of African towns and cities, and where greenery enters urban areas. These mosquitoes predominantly feed indoors at night.

Aedes aegypti is the world's most efficient mosquito transmitter of viruses. It lays its eggs in containers and thrives in small amounts of water that occurs in myriads of places including old tyres, blocked guttering, water containers, underground concrete structures or in a plethora of plastic waste that accumulates in the urban environment. Where there is high-density housing, few adult *Ae. aegypti* will fly further than 50 m from where they emerged, unless aquatic habitats are rare. This species predominantly bites in and around buildings during the day.

Box 2: Experimental houses for assessing how mosquitoes enter houses

Figure. Experimental houses in The Gambia.Experimental houses are a powerful tool for studying how mosquitoes enter homes. These houses, of a similar design to local homes, are built along a straight line, 10 m apart, each house differing in design to the reference house [23, 35]. At night, one or two volunteers sleep under an insecticide-treated net in each house, the current established best practice for malaria control. This way, the volunteers are protected from malaria, but the odours emanating from the houses attract mosquitoes indoors. Mosquitoes entering the house are captured in a trap with a light on it placed close to the bed of the volunteers. The following morning, mosquitoes collected in each trap are identified and counted. Repeat nightly collections are made for a set number of nights, usually four or five, and then each house typology is rotated, so that at the end of the experiment, each typology has been tested in each house position, for a similar number of nights. It is important to rotate house typologies between positions so that the effect of the typology, which is what one is interested in, can be separated from the effect of geographical position. If this was not done, one could not be certain whether any effect was due to the house typology or its position e.g. if it was close to or far away from a source of mosquitoes, such as a large area of irrigated rice. Volunteers are also rotated between experimental houses nightly, since some individuals are more attractive to mosquitoes than others. An example of how houses are rotated. using a Latin square. is shown below (Table).

Table: Schedule for testing interventions.

Block	Weekly house position				
	1	2	3	4	5
1	A	C	B	D	E
2	B	E	A	C	D
3	C	D	E	B	A
4	D	A	C	E	B
5	E	B	D	A	C

Where A, B, C and D are different house typologies.

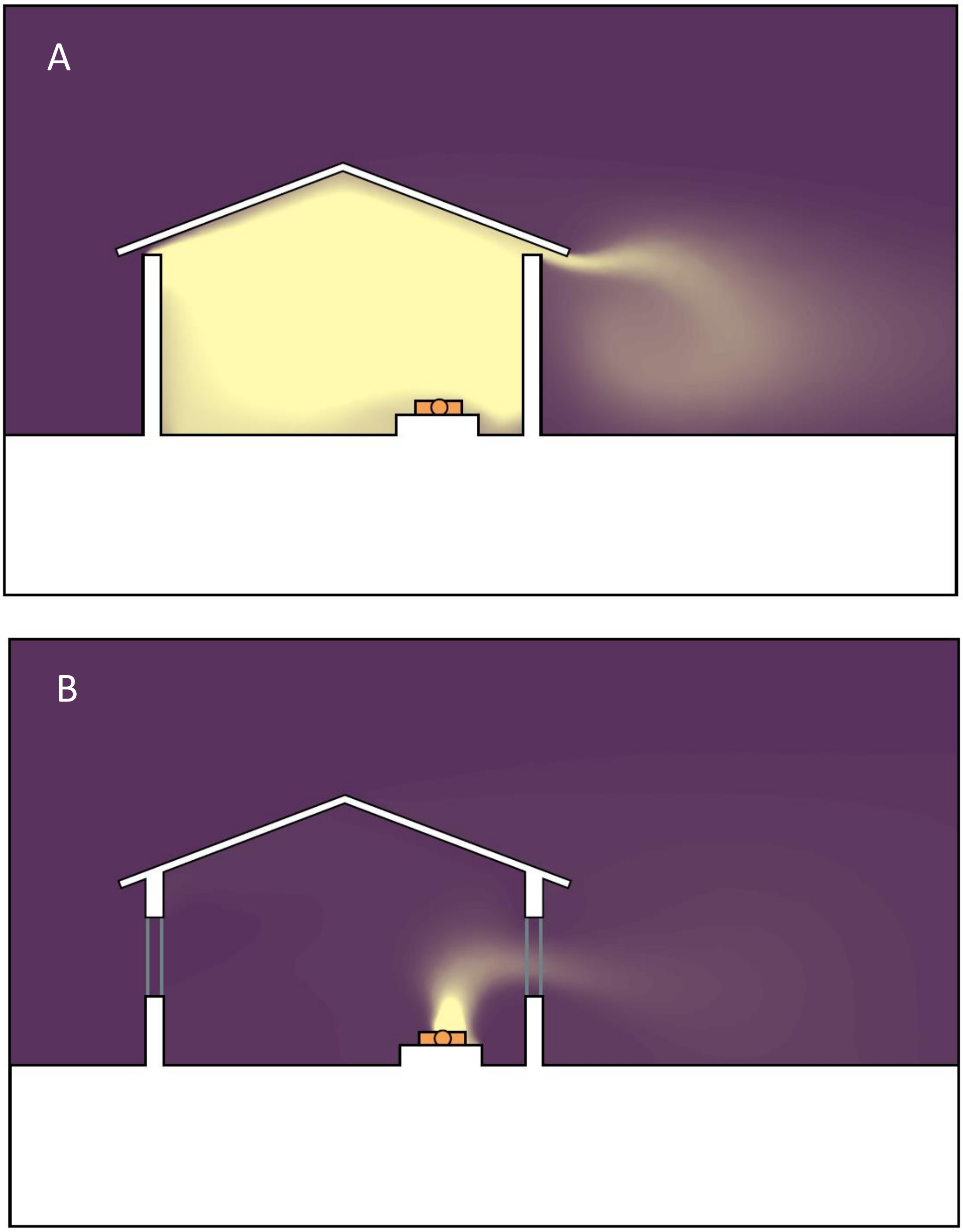
Figure legends.

Figure 1. Models of carbon dioxide (yellow) movement from a sleeping person (orange) in A, a metal-roofed mud walled house with open eaves and B, a similarly constructed house, but with closed eaves and two windows to improve ventilation.

Figure 2. DELIVER at a glance.

Figure 3. Importance of windows on opposite walls to encourage airflow through the building.

Figure 4. Framework for inter-sectoral action.



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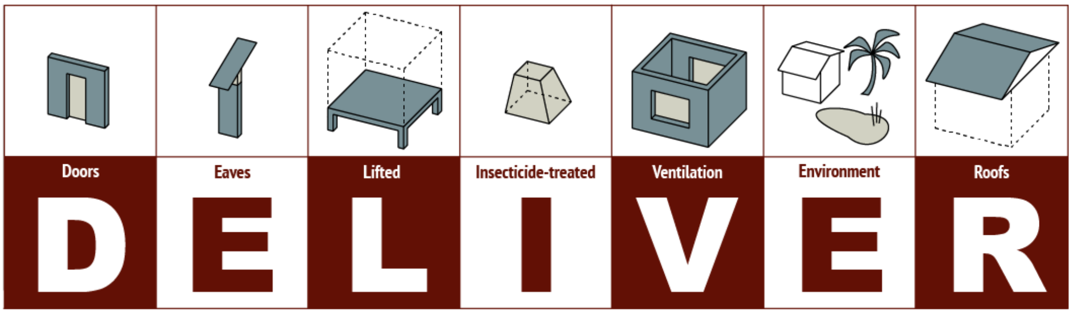

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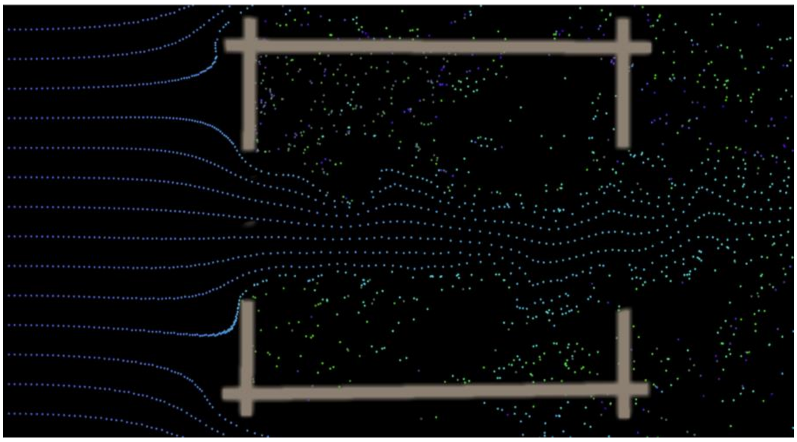

Figure 3. Importance of windows on opposite walls to encourage airflow through the building.

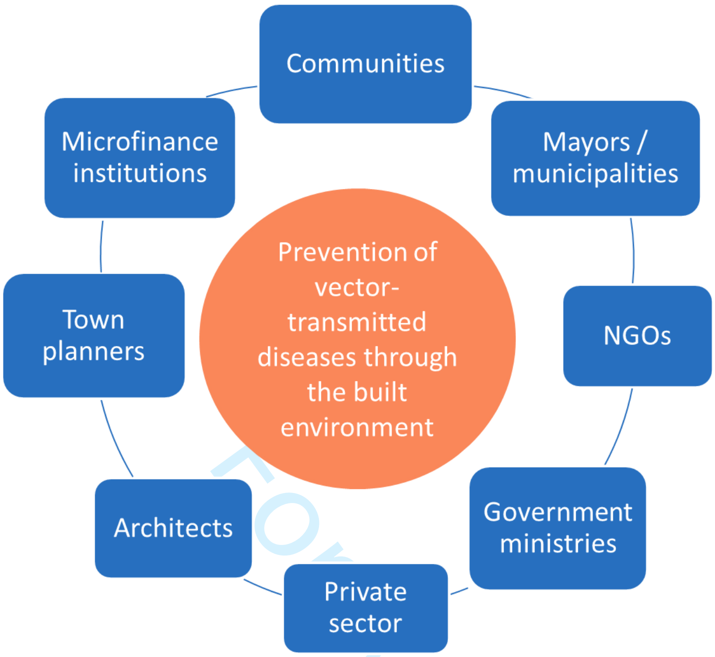

Figure 4. Framework for inter-sectoral action.