Chapter 15 Impacts of climate change on malaria vector control in Africa

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Abstract

There has been extensive consideration of how climate change may impact the distribution of vector-borne diseases; with a particular focus on malaria risk in Africa. Such analyses primarily consider how the "malaria map" will shift in response to changes in the environmental determinants of transmission, but rarely consider the equally if not more important question of whether climate change will impact the effectiveness of vector control measures. Here we hypothesize that the efficacy and ability to implement core vector control interventions for malaria could be significantly impacted by climate change due to direct and indirect impacts on mosquito vectors and interventions. We review current knowledge on the environmental dependency of current core interventions for malaria vector control including Insecticide Treated Nets, Indoor Residual Spraying and Larviciding. We explore how anticipated changes in temperature, rainfall and humidity could impact vector ecology, behaviour and resistance mechanisms; and the knock on effects of these changes for intervention efficacy. Finally we review potential indirect impacts of climate change on the ability to finance, implement and sustain vector control; with a focus on changes in human behaviour, land use, socioeconomic conditions and health systems. We conclude highlighting the need to build "climate-proof" strategies into future vector control planning.

Key words: Anopheles, climate change, mosquito behaviour, malaria interventions, Insecticide Treated Nets, Indoor Residual Spraying, temperature

1) Introduction

Climate change and infectious disease present some of the greatest challenges of our age. Their devastating impacts are increasingly clear(McMichael 2013), and have potential to impact every aspect of life including ecosystem function, human and veterinary health, food security, economic and political stability. While the independent impacts of climate change and infectious disease are sizeable; the greatest threats may arise from their interaction whereby the occurrence of one directly impedes ability to address the other.

We hypothesize this scenario is highly likely to arise in the context of mosquito vector-borne diseases (VBDs). VBDs such as malaria are a leading source of mortality and morbidity within Low and Middle Income Countries. Amongst the VBDs, malaria has the largest mortality burden; causing 627,000 deaths in 2021 alone (WHO 2021b). This burden is disproportionately concentrated in sub-Saharan Africa where more than 96% of malaria-related deaths occur; mostly in young children under 5 years old (WHO 2021b). While the upscaling of vector control interventions including Insecticide Treated Nets (ITNs) and Indoor Residual Spraying (IRS) have significantly contributed to the halving of malaria prevalence in Africa since the year 2000 (Bhatt *et al.* 2015), this disease still poses an unacceptable public health burden. Of particular concern, progress towards elimination has stagnated in recent years; with malaria prevalence and mortality staying level or even increasing in some African countries since 2015 (Noor and Alonso 2022). The causes for this slow down are complex, but likely principally driven by a combination of biological challenges such as insecticide resistance and outdoor biting in malaria vectors, and reduced investment, economic constraints, and disruption due to COVID (Lindsay *et al.* 2021, Sherrard-Smith *et al.* 2019a, Weiss *et al.* 2021, WHO 2018).

Numerous studies have demonstrated that malaria transmission is highly sensitive to climate [e.g (Caminade *et al.* 2014, Fall *et al.* 2022, Kelly-Hope and Thomson 2005, Mabaso *et al.* 2007, Reiner *et al.* 2015)] . This dependency arises because the survival, reproduction and behaviour of the major African malaria vectors (*Anopheles arabiensis, An.coluzzii, An. gambiae* and *An. funestus)* are highly sensitive to environmental conditions such temperature, humidity and rainfall (Afrane, Githeko et al. 2012, Parham, Pople et al. 2012)(Charlwood 2019). Also, malaria parasite development within vectors is temperature dependent (Paaijmans and Thomas 2013). Notably, temperature influences almost all mosquito life-history (Christiansen-Jucht, Parham et al. 2015, Agyekum, Botwe et al. 2021) and demographic processes (Parham, Pople et al. 2012). The sporogonic success (development of infectious stages) of malaria parasites within vectors is also temperature dependent; with the length of the extrinsic incubation period decreasing with temperature up to a maximum threshold beyond which sporogony fails (Beier 1998)(Murdock, Sternberg et al. 2016). The environmental dependencies of these key mosquito vector and parasite processes make malaria transmission highly likely to change with climate.

While the potential impacts of climate change on malaria have received much attention (Caminade *et al.* 2014, Diouf *et al.* 2021, Ermert *et al.* 2013, Gething *et al.* 2010a, Martens *et al.* 1999, Tanser *et al.* 2003b, Thomas 2004, Yamana and Eltahir 2013), there is another crucial question that has been largely overlooked: how effective will malaria vector control and elimination strategies be under modified climates? Here we hypothesize that the efficacy and ability to implement core vector control interventions for malaria could be significantly reduced by climate change due to direct and indirect impacts on mosquito vectors and interventions. If confirmed, such climate-mediated impacts could slow or even reverse progress towards malaria elimination even as the geographical area suitable for transmission in Africa may fall. To explore the potential for such a scenario, we first briefly review knowledge on how climate is expected to change in Africa, and its potential impact on transmission.

1.1 Future climate change predictions for Africa

While the effects of climate change will be global, it is hypothesized that sub-Saharan Africa is particularly vulnerable to severe and catastrophic impacts due to extreme reliance on small-scale rain-fed agriculture, socio-economic constraints and other factors (Connolly-Boutin and Smit 2016). Many studies have attempted to characterize and forecast the types of climate change anticipated in different regions of Africa; with predictions often varying between regions. Such predictions are generally derived from fitting a range of different Global Circulation Models (GCMs) to a series of Representative Concentration Pathways (RCPs) as proposed by the Intergovernmental Panel on Climate Change to reflect plausible future greenhouse gas emission scenarios (IPCC 2020). Key outputs of such forecasts are expected temperatures and precipitation patterns.

It is expected that temperatures in southern Africa may rise faster than the global average; generating a much higher frequency of heatwaves and droughts (Chersich *et al.* 2018). For example, a model developed for the Eerste River in South Africa model predicted that climate change in the 'near' (2022-57) and 'far' (2058-2093) future will increase evaporation and decrease rainfall by 2% and 8% respectively, leading to a reduction in water availability between 8-18% (Du Plessis and Kalima 2021). Similar modelling of the hydrology of the Kabombo sub-basin within the Zambezi Basin indicates that stream flow will become much more variable; and decrease by up to 3% even under intermediate scenarios (RCP 4.5);(Ndhlovu and Woyessa 2021). Thus the overall assessment for southern Africa is much warmer and drier conditions.

Predicted impacts of climate change are more variable across the East African region. Specifically, predictions of the magnitude and direction of climate impacts vary somewhat between different GCM and RCP scenarios. Many East African countries are already classified as "water stressed", and are expected to become increasingly so as climate changes. For example, per capita water availability is expected to fall below scarcity levels in Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Uganda, Tanzania and Zambia by the end of the century (Adhikari *et al.* 2015). This is based on predictions of temperature rises between 0.9-3.4 ^{o}C by the 2060s, and 1.3-5.5 ^{o}C by 2090s (Adhikari *et al.* 2015). However, there is some discrepancy between predictions depending on the modelling approach, focal area and scale applied. One study of future rainfall over the Lake Victoria region of East Africa predicted no significant change in mean monthly rainfall by the 2040s, and only a slight increase by 2075s (Akurut *et al.* 2014). While changes to precipitation across East Africa may be locally variable, there is consensus that temperatures will rise.

Analysis of time series data from the in Sahel region of west Africa indicate there has already been a substantial long-term decline in rainfall and increasing temperature between 1970-2000 (Ben Mohamed 2011). The ability to predict future climate is uncertain given some existing models do not fit well to historical data (Ben Mohamed 2011). However mean temperatures are expected to rise by at least 1-1.5^{o}C in the medium term (Amoussou, Awoye et al. 2020; Diedhiou, Bichet et al. 2018), and potentially considerably more in some areas (Chou *et al.* 2020). Predictions about rainfall are more variable, but there is an expectation of substantial alterations in frequency, seasonal duration and intensity of precipitation. For example, daily extremes in rainfall are expected to rise in the Mono Basin in Togo (Amoussou, Awoye et al. 2020). More heatwaves of longer duration are predicted throughout the region, but with an intensification of rainfall in some areas and considerable drying and increase in drought conditions in others (Diedhiou, Bichet et al. 2018). General trends and differences are evident between the four agro-ecological zones in Sahel region (UNHCR 2022). Higher temperature increases are projected for arid and semi-arid zones in the North compared to subhumid and tropical zones. However the subhumid and semi-arid zones will experience the largest increase in the proportion of 'very hot days' (e.g temperature > 35^{o}C) (UNHCR 2022). Finally while the number of heavy precipitation days will decline in the northwest, pronounced increases are expected in the eastern Sahel (e.g Northern Chad, Niger, Nigeria and Cameroon). Although predictions for specific regions are variable, substantial changes to climate are expected across the continent as whole; characterized by rising temperature, substantial shifts in rainfall and a higher frequency of extreme weather events.

1.2 Predicted impacts of climate change on malaria in Africa

The potential impacts of climate change on malaria in Africa have been investigated for more than 20 years (Martens *et al.* 1999, Tanser *et al.* 2003a). Early work focussed on the use of biological models to estimate to the geographical area suitable for malaria transmission based primarily on temperature requirements of mosquitoes and parasites (Martens *et al.* 1999). Such models predicted that climate change would lead to substantial increases in malaria distribution and people at risk. For example, one model estimated that approximately 300 and 150 million more people would be a risk of *P. falciparum* and *P. vivax* respectively by 2080 due to climate change (Martens *et al.* 1999). However, these models were subsequently questioned due to their failure or incomplete incorporation of other key environmental drivers of transmission (e.g rainfall). Later work using more complex spatiotemporal models predicted less dramatic changes to the African malaria map; with little change predicted in the latitudinal range, but altitudinal increases (Tanser *et al.* 2003a). This and other work indicated a more complex pattern of epidemiological impacts; including predictions of significant reductions in transmission in some parts of sub-Saharan Africa (Ermert *et al.* 2013, Gething *et al.* 2010b, Lafferty 2009, Thomas 2004, Thomas *et al.* 2004). The need to incorporate more detailed consideration of related changes in land use, urbanization and socioeconomic factors has also been highlighted (Caminade *et al.* 2014, Gething *et al.* 2010a, Yamana and Eltahir 2013).

Recent models have attempted to incorporate greater complexity and detail on the specific nature of metereological changes. Early models based on simplified assumptions and generalization of rainfall effects have been replaced by more sophisticated approaches based on explicit consideration of hydrology (e.g. water flow, concentration and evaporation across landscapes), land use change, and with predictions made at a finer scale. Such models have reinforced the prediction that increasingly warmer and drier conditions will reduce the length of the malaria transmission season in West Africa, but will increase the risk of highland malaria in East Africa (Alonso *et al.* 2011, Caminade *et al.* 2014, Diouf *et al.* 2021, Ermert *et al.* 2013, Leedale *et al.* 2016, Yamana *et al.* 2016). As an example, one study in the Western Ugandan Highlands found that that extreme flooding was associated with a 30% increase in the risk of a person having a positive malaria test (Boyce *et al.* 2016); highlighting the additional risk expected in areas where climate change is expected to increase these events.

In combination, this body of work indicates that the geographical area in which malaria transmission can occur in Africa is unlikely to significantly expand due to climate change; with substantial contractions possible in some areas. However, most models so far have primarily focussed on the direct biological impacts of climate change on parasites and vectors, and not the wider impacts on control activities and health systems. Consideration of these factors may give a very different perspective on the how the public health impact of malaria will respond to climate change. As highlighted by (Mordecai *et al.* 2020), the primary public health impact of climate change on VBDs may arise not through expansions of the "malaria map", but increased exposure within stable areas of transmission. One economic analysis suggested the cost of in patient treatment for malaria as a proportion of annual health expenditures per 1,000 people could rise by up to 20% within some African countries (Egbendewe-Mondzozo *et al.* 2011). Whether detrimental impacts of this magnitude or greater will arise will ultimately depend on if and how climate change will impact the efficacy and ability to implement surveillance, control and treatment.

2) Impacts of climate change on vector ecology and transmission ability

2.1 Importance of temperature to vector fitness and transmission potential

Climate change is expected to alter the distribution, abundance and species composition of African malaria vectors because their reproduction, survival, behaviour and pathogen transmission capacity are highly sensitive to environmental conditions. Notably, temperature influences almost all mosquito life-history (Agyekum *et al.* 2021, Christiansen-Jucht *et al.* 2015) and demographic processes (Parham *et al.* 2012). Temperature effects are often curvilinear – with a fitness trait or demographic rate increasing with temperature up to maximum followed by a rapid decline (Agyekum *et al.* 2021). For example, the speed of larval development in the laboratory accelerates with temperature; with development period of *An. gambiae sl*. being ~10 days shorter at 36C compared to 25^{o}C. However, development is significantly impaired at higher temperatures, with no larvae surviving at $\geq$ 38C (Agyekum *et al.* 2022, Bayoh and Lindsay 2003, 2004). At the adult stage, survival, fecundity and the length of the gonotrophic are reduced at high temperatures (Agyekum *et al.* 2021). Climate change is expected to increase not only mean temperatures across Africa, but also variability in daily temperatures. Increased temperature variability is difficult for ectotherms to cope with (Paaijmans *et al.* 2013); and may further impair population viability under climate change.

Rising temperatures may also affect the susceptibility and competence of vectors to malaria infection. The sporogonic success of malaria parasites is also temperature dependent; with the length of the extrinsic incubation period (EIP) decreasing with temperature up to a maximum threshold beyond which sporogony fails (Ohm *et al.* 2018). For example, models fit to laboratory data indicate that the EIP of *P. falciparum* in *An. stephensi* falls from 16.1 to 8.8 days as temperature rises from 21°C to 34°C (Stopard *et al.* 2021); with no sporogonic development above 35°C (Shapiro *et al.* 2017). Experimental studies indicate that temperatures rises as expected under climate change will decrease the vectorial capacity of *An. gambiae* by reducing parasite sporogonic success. Laboratory experiments on *An. gambiae* and *An. stephensi* indicated that their vectorial capacity could be reduced by 51-89% with increases in mean temperature from 27°C to 30°C (Murdock *et al.* 2016). Furthermore, experimental studies show that Anopheles immune responses that might impair parasite development are also temperature dependent (Murdock, Moller-Jacobs et al. 2013, Murdock, Blanford et al. 2014). Taken together with projected impacts on mosquito demography, this suggests that temperature increases as expected under climate change will have complex and diverse impacts on malaria vector ecology and transmission potential.

While temperature rises will certainly influence malaria transmission, the specific nature of these impacts will vary between settings depending on whether they move local conditions either into or above the optimal threshold for mosquitoes and/or parasites development. Additionally, the effect of temperature may be offset or mitigated by concurrent changes in rainfall. As reviewed above, climate change may lead to much heavier rainfall and flooding in some areas of Africa, and considerable drying and drought conditions in others. Such changes could, for example, boost mosquito populations even in areas where temperature ranges were approaching the upper threshold for their survival. Additionally, the moving of climatic conditions into the optimal temperature range for sporogony may have little impact on transmission if this is accompanied by substantial drying and reduction of habitats for mosquito oviposition. In summary, while temperature will certainly play a crucial role in determining how malaria transmission will be altered by climate change; it's impacts must be evaluated within the wider context of concurrent conditions.

2.2 Impact of climate change on malaria vector species composition

Whilst all African malaria vectors will be exposed to climate change, impacts will likely vary between species due to differences in their innate habitat preferences and physiological tolerances. In addition to the four primary native African vector species (*An. arabiensis, An. coluzzii, An gambiae* and *An. funestus)*, the major Asian malaria vector *An. stephensi* has now been detected in the Horn of Africa (Sinka, Pironon et al. 2020). All of these vector species differ in ecology, behaviour and environmental adaptations in ways that could modulate their response to climate change (Table 1). First, changes to rainfall and humidity are likely to favour some vector species over others. This could arise through interspecific variation in physiological tolerance such as resistance to desiccation and capacity to store water being favoured (e.g Table 1). It has been hypothesized that variation in these physiological traits explains why *An. gambiae* are more likely to be found in wet, saturated environments, and *An. arabiensis* in drier environments (Lindsay *et al.* 1998). Additionally, shifts in species composition could arise due to changes in the availability and diversity of aquatic larval habitats under climate change. Typically *An. gambiae* prefers to use small, temporary aquatic habitats for oviposition, while *An. funestus* is associated with larger and more permanent habitats (Kahamba *et al.* 2022) . The invasive *An. stephensi* prefer artificial container habitats in urban settings (Sinka *et al.* 2020). In areas where climate change leads to drying, *An. funestus*, and *An. stephensi* may have an advantage because their larval habitats are most likely to persist (because the former because it uses larger and more stable habitats and the latter because people may increasingly store water around houses when rainfall is limited). In contrast, a proliferation of small, temporary puddles in areas where climate change increases rainfall may benefit *An. gambiae.*

Changes in vector species composition due to climate change will also be determined by the extent of temperature rise. *Anopheles arabiensis* is generally considered better adapted to survival at high temperatures and more resistant to desiccation than *An. gambiae* (Table 1). *Anopheles funestus* may have similar or higher capacity to endure high temperatures than *An. arabiensis (*Table 1). Few studies have directly compared the environmental tolerances of African vector species with that of the invasive *An. stephensi;* probably because until recently they did not co-occur in the wild. However, a recent model based on data from seperate experiments suggests *An. stephensi* has a higher temperature optimum than *An. gambiae* (Villena *et al.* 2022), and is considered better adapted to warmer temperatures than *An. gambiae* (Mordecai, Ryan et al. 2020).

Of all African vector species, *An. funestus* may be the best adapted to dry conditions due to its longer persistence throughout the dry season, higher dessication resistance than *An. arabiensis* (Table 1) and additional adaptations such as aestivation which can facilitate survival through prolonged hot, dry periods (Charlwood, Vij et al. 2000, Huestis and Lehmann 2014). However *An. stephensi* is also likely to thrive in the warmer and drier conditions expected with climate change. In the Horn of Africa, this species has now been detected year round including in extremely hot months in Djibouti (Seyfarth *et al.* 2019). Additionally unlike native African vector species, *An. stephensi* is highly adapted to urban environments (Mordecai, Ryan et al. 2020). Consequently the concurrent impacts of climate change and increasing urbanization (section 5.2) may drive the expansion of this highly efficient vector across urban settings in Africa

In addition to variation in climate responses between vector species, there can also be substantial intraspecific variation in environmental tolerances between populations. Several studies have documented associations between dessication and chromosomal inversions within African vector species (Fouet *et al.* 2012, Gray *et al.* 2009). This inter- and intraspecific variation in mosquito adaptations to climate means that malaria vector communities under future climate change scenarios in Africa are likely to be radically different from those at present.

Table 1 – Differences in thermal tolerances of current (*An. arabiensis, An. coluzzi, An. gambiae* and *An. funestus*) and recently invasive (*An. stephensi)* malaria vector species in Africa. * indicate relative ability, eg '*' = highest ability, '**' intermediate ability, and '*' poorest ability.**

Species	***An. arabiensis***	***An. coluzzii***	***An. gambiae***	***An. funestus***	***An. stephensi***	Source
Larval survival at high temperature	***			**		(Agyekum *et al.* 2021, Lyons *et al.* 2012)

	***		**			(Kirby and Lindsay 2009)
Capacity for larval development at high temperature			*		**	(Villena *et al.* 2022)
Resistance to dessication		***	**			(Lee *et al.* 2009)
	***		**			(Gray and Bradley 2005)
	**			***		(Lyons *et al.* 2014)
Adult survival at high temperature	***		**			(Kirby and Lindsay 2004)
Persistence in the dry season				***		(Charlwood *et al.* 2000)

Several modelling studies have attempted to predict how the species composition and distribution of malaria vectors will respond to climate change in Africa (e.g (Akpan *et al.* 2019, Drake and Beier 2014, Olabimi *et al.* 2021, Tonnang *et al.* 2014). Key themes have been assessment of whether there will be a major shift towards more 'dry' or 'higher temperature' adapted species. For example, climate change has been hypothesized to favour *An. arabiensis* within the *An. gambiae* s.l group because it is the best adapted to dry conditions (Drake and Beier 2014). As this species is more exophagic and zoophilic than other members of the group (*An. coluzzii* and *An gambiae* (Lyimo and Ferguson 2009), a shift in this direction could reduce the suitability of indoor interventions such as ITNs and IRS. However, a study using ecological niche modelling predicted that climate change will significantly reduce the distribution of *An. arabiensis* by 2050 (Drake and Beier 2014). Thus *An. arabiensis* may not expand its range with climate change but could become an increasingly prominent vector within remaining foci of transmission. In contrast, a more localized modelling study suggested climate change will increase the range and density of both *An. arabiensis* and *An. gambiae s.s*. in Nigeria; primarily by facilitating increased invasion of Sahel and Sudan savannas within northern States (Akpan *et al.* 2019). It may not be possible to generalize about the predicted nature of shifts in African vector composition with climate change; as this likely depends on national and sub-national ecology and geography.

2.3 Implications of changes in malaria vector species composition for control

The nature and extent of climate-driven changes in malaria vector species composition could have significant impacts on the efficacy of interventions. Of particular concern is the potential for changes that favour vector species, genotypes and/or at behaviours with reduced susceptibility to interventions. There is evidence that the impact of the core indoor interventions of Insecticide Treated Nets and Indoor Residual Spraying varies between African vector species (Sinka *et al.* 2016). In particular, there has been extensive analysis of differences in the impacts of ITNs between highly endophagic and anthrophilic species like *An. gambiae* and *An. funestus* compared to the more zoophagic and exophilic *An. arabiensis* (Killeen 2014, Killeen *et al.* 2014, Kiware *et al.* 2012a, Kiware *et al.* 2012b). Modelling indicates that the magnitude of transmission reduction expected from ITNs varies substantially between these species on account of differences in their innate host preference, the presence of alternative hosts (cattle), and degree of outdoor biting (e.g (Killeen 2014)). Such impacts are complex; while more zoophagic species like *An. arabiensis* have lower vectorial capacity than highly anthrophilic species, they are also harder to suppress with indoor interventions like ITN and IRS because their behaviour means they come into contact with them less frequently. These theoretical predictions have been empirically supported by combined analysis of data from intervention trials; confirming that *An. funestus* is most heavily impacted by indoor insecticide-based interventions, followed by *An. coluzzii/gambiae* and then *An. arabiensis* (Sinka, Golding et al. 2016). Even if the geographic range of *An. arabiensis* decreases with climate change (Drake and Beier 2014), its potential dominance within remaining transmission settings could pose a challenge for current core interventions.

Finally, the impact of current interventions could also be eroded if *An. stephensi* continues to emerge and expand across African cities (Sinka, Pironon et al. 2020). Like An. arabiensis, this vector is quite exophilic and exophagic (Sinka, Pironon et al. 2020, Balkew, Mumba et al. 2021), and often bites early in the evening (e.g before 10pm, (Reisen and Aslamkhan 1978)). These behaviours will like reduce the impact of indoor interventions including Insecticide Treated Nets.. If climate change enhances the establishment of *An. stephensi,* there will be a need to expand the focus of control activities from rural to urban settings. The need to invest and implement in additional supplementary control measures will ultimately depend on which species are favoured under future climate scenarios.

3) Environmental dependency of vector control interventions

Climate change could directly affect control by modifying the efficacy and quality of interventions. Such effects could arise through environmental dependencies that are additional to those created by local vector ecology and insecticide resistance, and instead due to variation in product performance in different climates. Here we consider the potential for such effects with current WHO-recommended core (ITN and IRS) and supplementary (larviciding) vector control interventions.

3.1 Insecticide Treated Nets and Indoor Residual Spraying

Both Insecticide Treated Nets (ITNs) and Indoor Residual Spraying (IRS) work by targeting adult mosquitoes with insecticides inside houses. ITNs target adult females during host seeking, and IRS the females and males that rest indoors. Until recently, pyrethroids were the only class of insecticides approved for use on ITNs. Products based on pyrethroids, organochlorines, organophosphates, carbamates and neonicotinoids have been approved for IRS (WHO 2022). Whilst ITNs and IRS are recommended as core general interventions, there is considerable heterogeneity in their impact between African settings. For example, in recent trials, the IRS compound Actellic (pirimiphos-methyl) was associated with an 88% reduction of *An. funestus* in Kenya (Abong'o *et al.* 2020) but only 48% reduction of the same species in Mozambique (Wagman *et al.* 2021). Such differences may be due to variation in insecticide resistance and local vector ecology, but could also be due to local environmental conditions that impact product performance, durability and residual efficacy. Currently, the World Health Organization pre-qualifies vector control products including insecticides and treated nets on the basis of submission of evidence demonstrating impact on target vectors within environmental conditions of intended deployment settings (WHO 2021a). Whether similar efficacy and durability would be maintained under altered climatic conditions is unknown; and may vary between products and intervention classes. Studies from agricultural entomology indicate that the immediate and residual efficacy of some insecticide classes vary with temperature (Arthur 2013, Arthur *et al.* 2019) and humidity conditions (Gerken *et al.* 2021, Ranabhat and Wang 2020). As reviewed by (Sibanda *et al.* 2011), the stability of compounds used in IRS also varies with temperature, ultraviolet light and other environmental variables. Consequently it is reasonable to expect that environmental conditions contribute to local heterogeneity in vector control product efficacy; however the nature and epidemiological relevance of such effects are unknown. The WHO has highlighted investigation of the environmental contribution to vector control impact as a key priority for research, particularly in the context of mosquito behaviour and outdoor transmission (WHO 2022).

Variation in insecticide performance could be linked to temperature. As reviewed by Glunt et al, the toxicity of insecticides used in vector control often depends on ambient temperature (Glunt *et al.* 2013). This is hypothesized to be a function of temperature impacts on mosquito metabolism and nervous system function (Glunt *et al.* 2013). It has been further suggested that the standard temperatures used in WHO insecticide bioassays ($25^{o}C \pm 2^{o}C$ for ITNs, and $27^{o}C \pm 2^{o}C$ for IRS) may overestimate the temperatures at which mosquitoes are exposed to these interventions in the field (Glunt *et al.* 2013). The impact of temperature on toxicity appears to vary between insecticides classes (Glunt *et al.* 2013, Glunt *et al.* 2018, Glunt *et al.* 2014), with some potentially increasing with warming conditions and others falling or remaining stable. A recent systematic review supports a trend of decreasing toxicity at higher temperatures (Agyekum *et al.* 2021); which could lead to a deterioration of efficacy with climate change. As highlighted by (Glunt *et al.* 2013), more explicit consideration of the temperature profile of insecticide products and their fit to the environment of deployment could help mitigate against this. As discussed (section 5.1), these potential impacts of temperature on insecticides may interact with the willingness of people to use interventions like ITNs. This interplay between direct and indirect impacts on product efficacy and use will determine the impact of these interventions in warming conditions.

3.2 Larviciding

Larviciding is the regular application of microbial or chemical insecticides to water bodies or containers to kill the aquatic immature stages of mosquitoes (larvae and pupae). Larviciding is widely accepted as a supplement to the core interventions or ITNs and IRS. Several malaria endemic countries in Africa are now implementing larviciding; motivated by the need to incorporate additional approaches that also target exophilic, early biting and pyrethroid resistant vector populations (Tusting *et al.* 2013). Several larvicide products are non-chemically based (e.g the bacteria *Bacillus thurigenesis*), and thus not impaired by pyrethroid resistance. Evidence on the effectiveness of ground larviciding application for malaria control is well-established (Derua *et al.* 2019, Tusting *et al.* 2013). Notable examples include the use of the chemical Paris Green to eliminate *Anopheles gambiae* in Brazil and Egypt in 1940 and 1945s respectively (Shousha 1948, Soper and Wilson 1943), and a 90% reduction in malaria prevalence following larviciding in Sri-Lanka (Tusting *et al.* 2013). Despite this rich evidence base in support of this intervention, there has been limited consideration of how climate change may impact its impact and feasibility.

African malaria vectors spend between 7 to 27 days (Fillinger *et al.* 2003, Majambere *et al.* 2007, Nartey *et al.* 2013, Ng'habi *et al.* 2010, Ngowo *et al.* 2021) in aquatic habitats before transforming into terrestrial adults. During this period, larvae can be targeted by a range of methods including chemical insecticides, bacteria (eg *Bacillus thuringiensis israelensis* and *bacillus sphaericus*), surface oils and films, Spinosyns (metabolites extracted from the bacterium *Saccharopolyspora spinosa*) and insect growth regulators (eg novaluron and pyriproxyfen)(WHO 2013). These larvicides can be delivered through ground application (by hand or using conventional sprayers) or aerial application. Ground based larviciding is the most common delivery mechanism in sub Saharan Africa (Choi *et al.* 2019). The feasibility and impact of larviciding is highly environmentally dependent; and is recommended for use only in settings where larval habitats are 'few', 'fixed' and 'findable' (WHO 2022). There are several reasons why these criteria may be impacted by climate change. First, climate change will lead to heavy and prolonged precipitation and extensive flooding in some African settings. Ground delivery of larvicides may be hampered by extensive flooding which could limit access to aquatic habitats, dilute and wash away product (the latter may not be a concern if larvae are also washed out). Heavy precipitation and rainfall can also generate cryptic breeding habitats that are too numerous to treat. Additionally more frequent periods of heavy rainfall will necessitate repeated re-application of larvicides that is beyond the capacity of control programmes to deliver. The impact of larvicides in reducing malaria vector density is linearly correlated with coverage (Smith *et al.* 2013). Thus if larval populations are increasingly dispersed across a larger number of small and hard to reach habitats, the overall impact of larviciding will be compromised. This was observed in a programme in a flood zone in the Gambia, where larviciding had limited impact largely because ground teams were unable to reach and treat breeding habitats in a timely manner (Majambere *et al.* 2010). An explosion in the number of larval habitats due to prolonged precipitation will also make larviciding prohibitively expensive to implement at appropriate coverage.

In contrast to challenges posed by extreme rainfall, the prolonged drought conditions created in some parts of Africa due to climate changes may be advantageous for larviciding. Extreme drought would eliminate most small and ephemeral aquatic habitats; with mosquito populations being restricted only to a few remaining large and more stable habitats. These larger habitats fit more closely to the paradigm of 'few, fixed and findable', and will be easier to identify, access and treat. For example, a study by Charlwood et al (Charlwood *et al.* 2000) in the Kilombero Valley of Tanzania found that malaria vector larvae only persisted along the edge of river systems and larger permanent water bodies in the dry season. The concentration of larvae into these more limited and recognizable habitats as conditions become drier will make ground larviciding a more practical and cost effective intervention.

Another challenge for larviciding will be the increasing unpredictability of seasonal rains under climate change. The implementation of larviciding is easiest in the dry season when aquatic habitats are at their fewest. However, both the timing and duration of dry periods are less predictable as climate changes. For example, the monsoon season in parts of India may be lengthening with climate change (Karmakar and Pradhan 2020), thus decreasing the window over which larviciding is feasible.

Finally as with insecticides used for adult control, there is evidence that the efficacy of larvicides is influenced by the micro-climatic conditions under which they are deployed. *Aedes vexans* larvae collected from a field population in Germany were much more likely to be killed by Bti at a warm (25^{o}C) than cooler temperatures (5-20^{o}C); (Becker *et al.* 1992). However, another study found that Bti had a lower impact on *Ae. stimulans* in cool temperatures; presumably because larval feeding rates and thus biocontrol uptake was reduced (Walker 1995). To our knowledge, the impact of high temperatures on the efficacy of larvicides used for African malaria control is not well known.

3.3 Novel Vector Control Approaches

The efficacy of other novel vector control products currently in the development process could also be highly sensitive to local micro-climatic conditions, and thus vulnerable to change with climate. For example, the performance of spatial repellents is dependent on temperature, humidity and airflow conditions within the treated space (Ogoma *et al.* 2012). Studies in rural Tanzania (Ogoma *et al.* 2017) and Vietnam (Kawada *et al.* 2006) indicate spatial repellency is higher at warmer than cooler temperatures. This potential benefit of increased efficacy at higher temperatures could be offset off by faster evaporation and thus lower residual efficacy.

Attractive Target Sugar Baits (ATSBs) is another promising new vector control intervention whose efficacy is likely to be environmentally-dependent (Fraser *et al.* 2021). This intervention consists of device baited with an attractant lure and sugar source containing an insecticide. The effectiveness of this intervention likely depends on the attractiveness of ATSBs relative to other sugar sources fed on by mosquitoes in the environment (plants, flowers etc); with early work showing this intervention has high entomological impact in arid areas with limited vegetation [e.g Mali (Traore *et al.* 2020); Israel (Beier *et al.* 2012)]. Trials are currently underway to evaluate the epidemiological impact of ATSBs in differing eco-epidemiological settings (Eisele *et al.* 2022); and will show whether impacts is reduced when deployed in more vegetation rich settings. If so, this intervention may have greater impact under warmer, drying conditions that may arise under climate change.

Several novel (endectocides) and existing (insecticide-treatment) interventions are targeted at exophagic vector species that feed on cattle (e.g *An. arabiensis* and *An. stephensi*). An example is Ivermectin; an endectocide that can be used to treat helminths and other parasitic infections humans and livestock, and also kills mosquitoes that feed on treated hosts (Sylla *et al.* 2010). Mass drug administration of ivermectin to humans and/or cattle is being considered as a vector control tool. Preliminary trial results and modelling indicate this intervention will be most effective in areas of highly seasonal transmission (Slater *et al.* 2020). Climate-driven changes in malaria seasonality, and/or livestock husbandry and movement patterns could thus modify the likely coverage and feasibility of this strategy.

Climate change could also impact the effectiveness of existing and novel (e.g eave tubes) housing-based vector control interventions. These interventions usually involve screening or closing of mosquito entry points such as the open eave space between the roof and wall. In the case of Eaves Tubes, the eave space is filled in and PVC 'tubes' coated with insecticidal netting are inserted as points of air flow between the inside and outside of the house. Odours from people sleeping inside the house disseminate out through the Eaves Tubes; causing mosquitoes to be lured towards them and killed when landing on their surface. A recent epidemiological trial in Cote d'Ivoire indicated this intervention reduced malaria infection risk in children by 38% (Sternberg *et al.* 2021). In some cases, these interventions may increase indoor temperatures by reducing indoor air flow. Under warming conditions, the discomfort due to even small reductions in indoor airflow may reduce the acceptability of these interventions. This could be mitigated through additional house design modifications to ensure the comfort of the indoor microclimate.

As shown using these representative examples, microclimatic and other environmental conditions within the settings where novel vector control interventions are deployed are likely to affect their performance. Greater understanding of how new and existing products for malaria vector control will perform under future climate scenarios is needed.

4) Mosquito resistance strategies

There is growing evidence that resistance strategies mounted by mosquitoes are environmentally dependent. Focussing on ITNs and IRS, mosquito vectors have developed a variety of physiological resistance (Black *et al.* 2021) and behavioural avoidance strategies including early and outdoor biting and resting (Sherrard-Smith *et al.* 2019b). There is extensive evidence from agricultural entomology that the efficiency of physiological resistance to insecticides is temperature dependent; with the implications for future climate scenarios already well recognized (Pu *et al.* 2020). Notably, while some studies found physiological resistance in agricultural pests was impaired at high temperature, others reported an enhancement (Pu *et al.* 2020). This increased resistance at higher temperature was hypothesized to be due to pleiotropy or increased enzymatic activity in warmer conditions (Pu *et al.* 2020). In contrast, there has been relatively limited consideration of the impacts of temperature on insecticide resistance in malaria vectors. A recent systematic review suggested there may be a positive association between physiological resistance and temperature in Anopheles vectors (Agyekum, Botwe et al. 2021); suggesting mosquitoes will be less susceptible to insecticides in warmer climates. However, there is considerable heterogeneity in findings between studies. One laboratory study found that an insecticide resistant strain of *An. arabiensis* lived longer than a susceptible control line under high temperatures (Oliver and Brooke 2017); suggesting that climate could modify or even reverse the fitness cost of resistance mechanisms. However, another study showed that a resistant line of *An. funestus* exposed to Bendiocarb was more likely to die at high than intermediate temperatures, whilst deltamethrin was least likely to kill a resistant line of *An. arabiensis* at intermediate temperature than either hot or cold extremes (Glunt *et al.* 2018). The manner in which temperature impacts physiological resistance is thus complex, and may vary between mechanisms, species and insecticide classes.

In addition to physiological resistance, malaria vectors employ a range a behavioural avoidance strategies to evade indoor interventions. These can include a shift to biting earlier in the evening or in the morning when people are not protected by ITNs (Moiroux, Damien et al. 2014), increased zoophily and outdoor resting (Kreppel, Viana et al. 2020), and more outdoor biting (Reddy, Overgaard et al. 2011, Russell, Govella et al. 2011, Govella and Ferguson 2012). Similar to physiological resistance, these behavioural adaptations may be shaped by local environmental and microclimatic conditions. Recent work has shown that outdoor biting and resting can vary seasonally and in response to temperature. For example, *An. arabiensis* in Tanzania became more exophilic when temperatures indoors became warmer relative to outdoors (Ngowo *et al.* 2017), during the hot season (Kreppel *et al.* 2019, Kulkarni *et al.* 2006), and *An. gambiae sl* in Burkina Faso are more likely to rest indoors during the wet than dry season (Sanou 2020). Should such seasonal variation reflects how African malaria vectors could adapt their behaviour to warming conditions, suggesting there may be an increased need for outdoor interventions under future climate change scenarios.

5) Indirect impacts of climate change on vector control

In addition to the potential direct impacts described above, there are multiple ways through which the ability to implement vector control will be indirectly impacted by the wider social, ecological, economic and political consequences of climate change. Such indirect effects will be widespread and complex, and may have a larger impact on intervention strategy and efficacy than any of the more direct impacts outlined above. Here we highlight a few such factors that may have the greatest bearing on malaria vector control.

5.1 Human behaviour and use of interventions

Climate change could impact vector control efficacy by changing the human behavioural factors that influence intervention coverage and uptake. For example, the degree of protection obtained from ITNs is crucially dependent on usage. The decision to use an ITN is associated with micro-climatic conditions (Ahorlu *et al.* 2019, Pulford *et al.* 2011, von Seidlein *et al.* 2012). Specifically, users perceive ITNs to be less comfortable under warmer indoor temperatures and higher humidity (von Seidlein *et al.* 2012). ITN usage may fall during hotter periods of the year when people prefer to sleep outside where it is cooler (Guglielmo, Ranson et al. 2021). Similar effects could lead to a reduction in ITN usage with the warmer conditions brought by climate change.

In addition to influencing the decision of whether to use an ITN or not, climate change may influence the amount of time people are likely to spend under a net. Exposure to malaria vectors in outdoor settings in Africa happens in evening hours (e.g <10pm, before people go indoors to sleep); when people are engaged in outdoor activities such as cooking, eating or socializing (Finda *et al.* 2019, Monroe *et al.* 2019). Prolonged exposure longer into the night can also happen when people are engaged in specific types of outdoor work or socio-cultural events (Monroe *et al.* 2019). The total time spent outdoors in the evening and late night period is also influenced by microclimatic conditions. One study showed that residents of rural communities in Burkina Faso went indoors to sleep at later hours during the hotter period of the year (Guglielmo *et al.* 2021). By delaying the time of night at which users first go under an ITN, warming conditions could reduce the total amount of protection received from it. Improved understanding of the environmental factors that influence human behaviours and decisions on ITN use (Monroe *et al.* 2021) are needed.

5.2 Land use and urbanization

One of the largest expected impacts of climate change is on land use (IPCC 2020). Climate change is predicted to lead to large changes in land quality and use across the globe; including erosion and degradation in some coastal areas, and expansion of drylands with increasing desertification. Drying conditions combined with shorter more intense rainfall and extreme flooding events increase erosion and diminish soil quality (IPCC 2020). Changes to land type and soil quality will fundamentally impact patterns of land use and human activities; with several consequences for the vector control strategies.

Most directly, these changes will impact agriculture and food security. It is estimated that ~90% of agriculture in sub-Saharan Africa is dependent on rain and managed by small holders (Abraham 2018). Staple crops such as maize and wheat have already been negatively affected by recent climate change (IPCC 2020); with yields at further risk in the future. Additionally, reductions in water availability and distribution will impact livestock husbandry. This is in turn could impact the efficacy and feasibility of livestock-based vector control methods such as zooprophylaxis and endectocides (Donnelly *et al.* 2015) Adaptations such as crop diversification and irrigation will be required to mitigate against the most negative consequences of these changes (Abraham 2018). However, these strategies could also influence the efficacy and feasibility of vector control. For example, irrigation schemes and dams are known to have complex associations with malaria risk in Africa (Ijumba and Lindsay 2001, Keiser *et al.* 2005, Kibret *et al.* 2021, Kibret *et al.* 2017) Analysis of the literature indicates that dams may lead to increased transmission in highland or semi-arid areas of unstable transmission, but may be less important in areas of endemic transmission (Kibret *et al.* 2017). The creation of large irrigated areas may increase mosquito breeding sites, and make larval control more difficult (Karch *et al.* 1992).

Another mitigation response to diminishing crop yields arising from unpredictable weather conditions is heavier pesticide use. For example, small scale farmers in Rwanda reported increased use of pesticides as one of several common responses to mitigate the adverse impacts of increased drought and floods on their crops (Helwig *et al.* 2020). Pesticides used in agriculture are a major source of selection for insecticide resistance in malaria vectors (Chouaibou *et al.* 2016, Nkya *et al.* 2013, Nkya *et al.* 2014); thus their intensified use in response to climate change could erode the efficacy of ITNs and other insecticide-based approaches. Such an interplay will increase the already great need for stronger intersectoral collaboration between agriculture and public health under future climate scenarios.

Diminishing returns from small scale agriculture as a result of climate change have been linked to increasing migration to urban centres in several areas of Africa (Henderson *et al.* 2014, Henderson *et al.* 2017, Serdeczny *et al.* 2017). Currently urbanization is happening faster in Africa than anywhere else in the world; with up to 2/3 of the total population expected to live in urban areas by 2050 (OECD *et al.* 2020). Climate change poses specific risks to urban populations, particularly those living in informal settlements that are at increased risk of flood damage, socioeconomically deprived, and poorly connected to electricity and water infrastructure (Abraham 2018). These housing conditions could generate increased exposure to malaria and other vector-borne diseases (Mordecai *et al.* 2020). For example, rapid urbanization in Soweto led to more people living in flood plain areas (Abraham 2018); with these being ideal habitats for mosquito vectors. Urban dwellers, and particularly those living in peri-urban and informal settlements may increasingly turn to market gardening to enhance food security (Eigenbrod and Gruda 2015). This could increase malaria exposure in those living close to market gardens (e.g.(Yadouleton *et al.* 2010)); possibly due to the generation of larval breeding sites through agricultural activities.

Poor housing conditions in informal urban settlements may not only increase malaria risk (Tusting *et al.* 2015), but may make it more difficult to implement standard vector control measures including installation of ITNs and IRS. Some interventions such as larviciding may be more feasible and cost effective to implement in urban settings (Worrall and Fillinger 2011), whilst others like ITNs and IRS have lower usage in urban than rural settings (Ministry of Health *et al.* 2018). As described in section 2, the recent invasion of *An. stephensi* in East Africa poses an additional risk for malaria control in urban African settings (Sinka, Pironon et al. 2020). Unlike native African vector species, *An. stephensi* is highly adapted to urban environments (Mordecai *et al.* 2020). The unique ecology and behaviour of this vector, combined with it higher transmission efficiency, could require more tailored vector control interventions in urban settings. Sustaining vector control under future climate scenarios will require adapting current approaches to socio-economically disadvantaged populations in urban environments.

5.3 Economic and Political Factors

The ability to finance and implement large scale vector surveillance is fundamentally dependent on strong political will, governance infrastructure and economic security. As illustrated by the recent overwhelming resurgence of vector-borne diseases in Venezuela, even countries with a long and successful history of vector control can see rapid reversals during socio-economic and humanitarian crises (Grillet *et al.* 2019). Climate change is likely to increase vulnerability to such socio-economic shocks and lead to corresponding constraints on health systems and vector control programmes. These constraints may be further exacerbated by increased conflict (Adaawen *et al.* 2019, Freeman 2017), migration and increases in other infectious (Adekiya *et al.* 2020, Ahmed *et al.* 2018, Bryson *et al.* 2020, Charnley *et al.* 2022) and non-communicable diseases (Amegah *et al.* 2016).

The United Nations High Commission on Refugees estimates that 21.5 million people have been forcibly displaced each year since 2008 due to extreme weather events including floods, storms, wildlife and extreme temperature (Bilak *et al.* 2016). This number is expected to increase with climate change; with as many as 86 million internal climate migrants expected in sub Saharan Africa by 2050 (Clement *et al.* 2021). Refugees often face a considerably higher risk of malaria exposure and severe outcomes due to a myriad of factors including poor and insecure housing, infrastructure and limited access to prevention and treatment (e.g (Anderson *et al.* 2011, Charchuk *et al.* 2016, Hauser *et al.*)). There is some evidence that migration can lead to malaria spillover across border areas and local upsurges in areas where transmission was under control (e.g. (Rodriguez-Morales *et al.* 2019). Thus in the absence of access to healthcare including diagnosis and treatment, climate refugees may increasingly strain malaria control and compromise elimination activities. Development and implementation of more tailored diagnostics, treatments and vector control interventions for emergency contexts will be needed to sustain progress under climate change.

Sustaining and expanding malaria vector control under these more complex and economically constrained circumstances will be challenging. Already funding for malaria control is substantially below the level needed to meet global elimination targets, and has largely plateaued since 2012 (Lindsay *et al.* 2021). If health systems become even more stretched as climate changes, vector control programmes will increasingly be asked to deliver more effective interventions with less funding. Mass distribution of efficacious but relatively higher cost interventions that are recommended for use now (e.g some Next Generation Nets) may become increasingly unaffordable. Clearly, maintaining malaria vector control will require the adaptation of current approaches and development of new ones that are both effective and affordable under future climate scenarios.

6) Conclusions and recommendations

Consideration of the potential impacts of climate change on vector-borne diseases has so far focussed almost exclusively on assessment of the environmental determinants of transmission. Such analyses provide an essential foundation to understand how the area at “risk” of transmission may expand or contract; but on their own are insufficient to predict the nature of public health impacts. An equally important yet largely neglected question is how well our current and prospective control measures will function under altered climates; and how our ability to implement and sustain these approaches will be shaped by shifts in wider socio-environmental, economic and political factors that accompany this change. Within the context of malaria vector control in Africa; we have highlighted several routes through which the efficacy of interventions could be modified by the types of climate change predicted. A key theme is that climate change will have diverse and complex impacts across different regions of Africa, so that there may be no universal impact in all settings. Through synthesis of the varied biological and indirect impacts considered here, it is clear that climate change could have wide-ranging impacts on the implementation, feasibility and efficacy of vector control interventions in Africa. The overall impact of these changes on malaria control will depend on to what extent conditions for the “worst” versus “best” case scenarios are realized, as exemplified by the representative example in Box 1. At one end of the spectrum, climate change may enhance vector control through causing malaria vector populations to contract and reduce in abundance, and increasing the efficacy of some control methods. Alternatively, climate change could substantially erode vector control through favouring vector species and phenotypes that are harder to tackle with existing interventions, enhancing capacity for resistance, reducing the acceptability and use of interventions, and generating economic constraints that make it harder to deliver control programmes. The degree to which potential challenges can be offset by such advantages will fundamentally depend on the robustness of public health and other socioeconomic infrastructure. Clearly, there is a need to “future-proof” vector control strategies through more anticipation and integration of potential climate impacts into future planning. This will require going beyond modifications and tailoring of existing and currently developing interventions, to more ‘blue sky’ and integrated approaches that are able to mitigate the impacts of climate change on malaria and other environmental hazards at the same time. Just as there has been extensive consideration of adaptation of agricultural systems to climate change, similar forethought is required for adaptation of vector control strategies. In particular, the addition of new control strategies that may be less sensitive to the environmental conditions of deployment (e.g malaria vaccines) could greatly supplement and bolster control. While we focus on malaria in Africa, many of the issues raised here apply to the control of other mosquito-borne diseases that are controlled through use of similar interventions (e.g Aedes vectors of arboviruses). To better prepare and mitigate against the most negative impacts, we advocate for consideration of climate change impacts to be built into future vector control and public health planning.

Box 1: Speculative “best” and “worst” case examples of how climate change may impact malaria vector control interventions in Africa, based on information reviewed in this Chapter.

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Box 1: Speculative 'best' and 'worst' case examples of how climate change may impact malaria vector control interventions in Africa

		"Best Case"	*"Worst Case"*
Direct Biological Impacts	***Vector ecology***	-Contraction of vector distribution and abundance with drying -Reduction in vector survival and length of seasonal activity period due to unfavourable temperature and rainfall -Shifts in vector species composition towards species that are better adapted to dry conditions but easier to target with some interventions (e.g *An. funestus* by larviciding and indoor interventions)	-Increased mosquito vector abundance and longer seasonal activity in areas receiving increased rainfall -Shifts in vector species composition with drying towards species that are better adapted to dry conditions but harder to target with indoor interventions (e.g *An. arabiensis* and *An. stephensi*) -Spread of invasive An. stephensi (urban adapted, efficient transmission at high temperatures)
	Interventions	-Larval habitats may become fewer and more 'findable' under drying conditions; improving the feasibility of larviciding -Possible enhancement of some novel vector control tools (e.g ATSBS) under drier conditions	-Reduced toxicity and residual efficacy of some chemical and biological insecticides at higher temperatures -Lower coverage and need for more frequent application of larvicides with increasing rainfall /extreme weather events -Possible reduced feasibility or acceptability of some novel control strategies at higher temperature/lower rainfall
	Vector Resistance Strategies	-Reduced ability for vectors to mount energetically costly resistance mechanisms under environmental stress	-More effective physiological resistance to insecticides due to enhanced expression of detoxification genes at higher temperatures -Emergence of mosquito adaptations to warming conditions that also enhance insecticide resistance (e.g cuticle thickening as a strategy for desiccation resistance) -Shift to outdoor biting by mosquito vectors where warmer conditions reduce the suitability of indoor microclimatic conditions
Indirect Impacts	***Human Behaviour***		-Lower usage and effective coverage of ITNs due to changes in human behaviour and sleeping patterns at warmer temperatures
	Land use	-Changes in livestock keeping practices that reduce mosquito vector populations -Increasing urbanization enhances the feasibility and implementation of some vector control interventions	-Changes in livestock keeping practices that reduce potential for livestock-based interventions -Higher selection for insecticide resistance due to intensification of pesticide use as a strategy for minimizing agricultural losses due to adverse weather and drought conditions -Influx of urban migrants who are exposed to malaria vectors due to insecure housing, limited infrastructure and exposure to environmental risks
	Political and economic	Climate-driven reductions in malaria reduce the costs needed to run vector control programmes	-Rise in climate refugees who are at greater risk of malaria -Constraints on health systems due to rises in other health issues -Reduction in financing for control due to national and global economic constraints -Increased conflict and political insecurity impeding health services and control programmes