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TECHNICAL REPORT

SHIFTING BURDENS

MALARIA RISKS IN A HOTTER AFRICA



June 2019

This document was produced for review by the United States Agency for International Development. It was prepared by Fernanda Zermoglio (Chemonics International) and Sadie Ryan (University of Florida) and Michael Swaim for the Adaptation Thought Leadership and Assessments (ATLAS) Task Order No. AID-OAA-I-14-00013, under the Restoring the Environment through Prosperity, Livelihoods, and Conserving Ecosystems (REPLACE) IDIQ.

Chemonics contact:

Chris Perine, Chief of Party (cperine@chemonics.com)

Chemonics International Inc.

1717 H Street NW

Washington, DC 20006

ATLAS reports and other products are available on the Climatelinks website: <https://www.climatelinks.org/projects/atlas>

Cover Photo: USAID. 2015. A beneficiary of a USAID-funded net distribution project hangs a net in her house in Kisii County, Kenya.

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Prepared for:

United States Agency for International Development (USAID)

Adaptation Thought Leadership and Assessments (ATLAS)

Prepared by:

Fernanda Zermoglio (Chemonics International)

Sadie Ryan (University of Florida)

Michael Swaim

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ACRONYMS

DRC	Democratic Republic of the Congo
MODIS	Moderate-Resolution Imaging Spectroradiometer
NDVI	Normalized difference vegetation index
RCP	Representative Concentration Pathway
USAID	United States Agency for International Development

EXECUTIVE SUMMARY

OVERVIEW

Climate variability and change present both current and future risks to human health. For example, changes in temperature, precipitation, and extreme weather events alter the geographic range, seasonality, and survival of pathogens and the vectors that transmit them. Similarly, these events also increase human exposure to events such as floods, heat waves, and droughts, and put at risk health infrastructure necessary to reduce disease transmission (e.g., health centers, supply chains). Understanding how, when, and under what circumstances climate variability and change impact health outcomes is limited, especially in sub-Saharan Africa.

This study alone is not meant to guide programmatic decisions, additional field studies are needed for these findings to be used as predictive insights. Nevertheless, the purpose of this report is to:

- 1) Increase understanding of the influence of climate variability and change, specifically, rising temperatures on malaria exposure of populations in sub-Saharan Africa
- 2) Provide public health decision-makers and stakeholder practitioners with information to make decisions about malaria planning and programming under a changing climate.

Temperature impacts both the life cycle and habitat of malaria-carrying mosquitoes (genus *Anopheles*) and parasites. Warmer temperatures may result in new locations suitable for malaria transmission, while currently suitable locations may become too hot, leading to reductions in malaria's seasonal duration and overall risk. This report analyzes the shift in malaria transmission suitability based on projected temperature rise in the short, medium, and longer term (2030s, 2050s, 2080s), as well as the influence of those changes on the number of people at risk.

A NOTE ON METHODS AND DATA SOURCES

This analysis explores vector suitability considering future temperature increases due to climate change under several future climate scenarios derived from climate model projections. The empirical model is derived from temperature response curves for the mosquito species *Anopheles gambiae* and the malaria pathogen (*Plasmodium falciparum*). The metric for transmission suitability, called R_0 , which is scaled from 0 to 1, is described in quantiles; the top quantile (top 25 percent) of the curve is selected to represent the range of temperature in which transmission suitability is expected. This conservative measure of the overall temperature curve is used because it corresponds visually to existing maps of ongoing transmission under current temperatures.

A multimodel ensemble representing future climate was compiled from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive, downscaled using a Change Factor (CF) approach and sourced from Navarro-Racines et al. (2015). The ensemble allows exploration of a range of climate projections under two representative concentration pathways (RCP 4.5 and RCP 8.5) for three time periods: the 2030s, 2050s, and 2080s. Arid areas that preclude *Anopheles* development are excluded using the Moderate-Resolution Imaging Spectroradiometer-derived (MODIS) normalized difference vegetation index (NDVI) values for 2016.

Population data are derived from the Gridded Population of the World, Version 4.11 (GPWv4.11) (CIESIN 2016). Baseline calculations are from 2015 data, while projected population data are extracted from the 2020 layers.

KEY FINDINGS, IMPLICATIONS, AND HOTSPOTS

While the analysis focuses on projections of rising temperatures for the 2030s, 2050s, and 2080s, current climate variability and continually rising temperatures are already altering the distribution of malaria across sub-Saharan Africa. The following outlines projected changes captured in this analysis.

OVERALL

- Temperatures across the continent will rise between 0.9°C (under RCP 4.5, the best-case scenario by the 2030s) and 4.5°C (under RCP 8.5, the worst-case scenario by the 2050s), with some spatial variability by region (see Table 1, page 17).
- Under both temperature increase scenarios, RCP 4.5 and RCP 8.5, an additional 16 million to 18 million people will shift from areas of no suitability risk (0 months) to endemic malaria exposure (10–12 months) in sub-Saharan Africa by the 2030s, with a significant portion located in East Africa.
- Approximately 47 to 58 million people in West Africa will see reduced endemic risk (10–12 months) due to temperatures exceeding the thermal thresholds for mosquitoes by the 2030s. However, they will still experience marginal to moderate risk (1–6 months). Under the best-case scenario (RCP 4.5), there will be a net increase of approximately 65 million people at any risk of malaria transmission in West Africa (those moving from endemic, seasonal, or no suitability to marginal/moderate malaria exposure).
- Between the 2030s and 2050s, rising temperatures will likely increase the southern range of seasonal suitability (7–9 months) for *Anopheles* mosquitoes into parts of Southern Africa that were not previously suitable (0 months), adding approximately 3 to 26 million people at risk from seasonal malaria exposure.

NEW AREAS OF MALARIA SUITABILITY

- There are several areas across Africa currently unsuitable for malaria that will likely become areas of endemic (10-12 months), seasonal (7-9 months), moderate (4-6 months), or marginal (1-3 months) malaria suitability based on projected increases in temperatures by as early as the 2030s and beyond.
- Regions of endemic (10-12 months) suitability will likely emerge in the center of the continent, the East African highlands, the Lake Victoria region, and northern Zambia, by the 2030s, becoming more pronounced in the latter part of the 21st century (2050s and 2080s).
- Concentrated regions of seasonal (6-9 months) suitability will likely emerge in central Angola, northwestern Zambia, northern Tanzania, and the southern coast and northern region of Mozambique by the 2030s. These regions will either remain as they are currently or will move both northward and southward into the highlands of Ethiopia and Southern Africa toward the latter part of the 21st century (2050s and 2080s).
- In other areas the malaria season will likely be extended (for example, from seasonal (7-9 months) to endemic (10-12 months)) as temperatures increase (Figures 9, 11, and 13).
- Areas where spring and autumn are currently too cold for the reproduction of malaria vectors may become more suitable in the future, thus extending the malaria season. In these areas, increases in temperature may not impact midsummer malaria incidence greatly, but may result in a longer malaria season. In some cases, malaria may shift from being a seasonal disease burden (7–9 months) to an endemic burden (10–12 months).
- Areas where seasonal suitability will likely become endemic, thus extending the malaria season, include hotspots for the 2030s such as the coasts of Central Africa (Gabon, Congo, Cameroon, central Tanzania, and northern Mozambique). A hotspot for the 2030s is East Africa, which will see an increase of approximately 29 to 30 million people at risk. This is reflected in the changes projected for Uganda, where an additional 4 to 8 million people will live under conditions of endemic suitability relative to the approximately 4 million living under these conditions today (Figure 10).
- Areas where moderate or marginal suitability will likely become endemic include higher-elevation regions of Southern and East Africa. Areas likely to be impacted by these changes include northern Angola, southern DRC, western Tanzania, and central Uganda by the 2030s. By the 2050s, impacted areas may extend into western Angola, the upper Zambezi River Basin, and northeastern Zambia, as well as becoming more concentrated along the East African highlands (Figure 11). These changes could affect approximately 18 to 24 million people in East Africa alone as early as the 2030s and could add 6 to 11 million people to the approximately 2 million currently living under endemic conditions in Tanzania alone across all future time periods.
- Areas where moderate or marginal suitability (1-6 months) will likely become seasonal include the Southern Africa region: Zambia, Malawi, and Tanzania, eastern South Africa, Botswana, the highlands of Zimbabwe, northern Mozambique, and the Zambezi River

Basin (Figure 13). These changes will put approximately 17 to 21 million people at increased risk from transmission in Southern Africa under the best-case scenario (RCP 4.5) by 2030, adding approximately 9 to 12 million people to those currently living in seasonal conditions of risk in Zambia alone across all future time periods and scenarios (Figure 14).

SHORTENING OF MALARIA SEASON

- There are several areas where the months of suitability for malaria transmission will be reduced from endemic to seasonal or to moderate/marginal (Figure 15).
- In West Africa approximately 47 to 58 million people will see reduced endemic risk (10–12 months) but will still experience marginal to moderate risk (1–6 months) due to temperatures exceeding the thermal thresholds for mosquitoes. In Nigeria alone, these changes will shift approximately 24 million out of endemic conditions of exposure to seasonal conditions by the 2030s (Figure 16). The net change in numbers of people at any risk of malaria transmission (those moving from endemic, seasonal or no suitability to marginal/moderate malaria exposure) will be an increase by approximately 65 million people in West Africa by the 2030s under the best-case scenario (RCP 4.5).

CONCLUSIONS AND INSIGHTS FOR ACTION

This analysis offers a new view of potential changes in malaria seasonality due to projected rising temperatures. This study alone is not meant to guide programmatic decisions. Additional field studies are needed for these findings to be used as predictive insights, and it is important to consider the role of temperature as a driver of malaria burden when combined with other likely drivers such as population movement and malaria control and elimination interventions. Some of the implications of this research for action and strategic decision-making are discussed below.

TARGET ON-GROUND SURVEILLANCE AND RESPONSES TO CHANGING EPIDEMIOLOGY

There are many examples across sub-Saharan Africa where investments have shown marked progress in malaria control strategies. These gains, however, could be compromised if future investments do not consider the role of rising temperatures in changes to epidemiology. The analysis presented here offers several insights of relevance to these risks:

- Targeted and informed on-the-ground surveillance: Knowing where and when changes in burden are likely to take place offers the opportunity to geographically target monitoring of climate change interventions.
- Addressing the risk of epidemics: Where malaria suitability is likely to shift from nonexistent to newly suitable, whether seasonal or endemic, the risks are critical. When local populations have little or no immunity to the disease, malaria suitability changes can often lead to epidemic ‘flares’, especially among vulnerable groups such as pregnant women, children, and the elderly. Surveillance data allows for the preparation

of a timely response before the outbreak of epidemics and can guide decisions around distribution of malaria services and their use by impacted communities.

- Adjusting current management and control interventions: Surveillance information offers an opportunity to adjust the investment time frame (seasonal to year-round, or vice versa), optimize vector control, and improve case management, with the evidence base to support these actions. Pinpointing regions where transmission could be reduced lowers the cost of interventions and provides an opportunity to reach pre-elimination or elimination.
- Addressing malaria elimination: In areas where the months of malaria suitability will decrease, there is an opportunity to invest in targeted surveillance and response systems to identify, track, and respond to malaria cases in remaining transmission foci (e.g., infected mosquitoes or affected patients). Elimination efforts informed by these analyses could better target resources to reduce the potential burden of additional cases through timely treatment and preventive measures.

IMPROVE A COUNTRY'S CAPACITY FOR COLLECTING AND USING INFORMATION AT THE NATIONAL LEVEL

Significant progress has been made to improve data and information available for malaria programming, management, and evaluation via investments in strengthening routine disease reporting and health management information systems. Nevertheless, challenges remain, including the need to improve reporting rates and shorten the lead times to inform planning and monitoring to near real-time.

Understanding the influence of rising temperatures on vector ranges and disease dynamics is an important first step in building the knowledge base to evaluate the impact of climate on malaria incidence and to inform investments. This analysis indicates that, as temperatures rise, even by around the 2030s, important changes are anticipated in *Anopheles* transmission suitability, both in changes in seasonality and the range of malaria vectors. Importantly, temperature-driven changes in vector dynamics are themselves mediated by direct and indirect environmental and societal factors, such as changes to ecosystems, land use, and others that may reduce or amplify the vulnerability of certain groups to malaria risks. New methods of data collection, integration, and analysis will require cross-ministry investment, information-sharing, and analysis, and will be critical to understanding the complexity of the links among these factors.

Public health observatories, many already operational around the world, could provide a model for scaling up analysis of health data in the context of other climate and environmental parameters. In general terms, health observatories are virtual platforms that can link health systems to other relevant information, such as weather data, to support health policies and planning. According to the WHO (2016), “their purposes vary but the major objectives are: monitoring health situations and trends, including assessing progress toward agreed-upon health-related targets; producing and sharing evidence; and supporting the use of such evidence for policy and decision making.” Such observatories could also help with the timely

use of remotely derived weather and climate information to inform investments and strategies in malaria control.

Establishing a health observatory in countries where malaria patterns are changing rapidly could:

- Formalize agreements around interdepartmental and inter-ministerial collaboration and data sharing: Governmental health agencies often lack the mandate to coordinate collaboration and share data with other stakeholders. However, in order to make meaningful advances on research and monitoring to understand climate and weather impacts on epidemiology, it is essential to have access to historical climate and trend information, together with health data related to past events. Improved communication and collaboration across the sector, especially the integration of information from various sectors and sources, will be critical to strengthening understanding of vector changes and rapidly evaluating the potential risks from specific weather events to a country, region or health post.
- Leverage information technology: Gains in Geographic Information Systems and earth observations, along with the development of tools capitalizing on these technologies, can support efforts to scale as well as to fine-tune analyses focused on improving the timeliness and completeness of surveillance during critical periods.
- Build a community of practice: It will be critical to go beyond the traditional program partners to integrate partners who could explore the links between environmental parameters of interest (including weather and climate) and strategic and programmatic decisions that need to be made in a malaria program.
- Advance research on critical outstanding questions: Research priorities include, but are not limited to, understanding more fully the links between increased temperature, changing rainfall patterns, extreme weather events, and malaria; determining specific climatic thresholds of concern for surveillance; and improving analytic tools to visualize cross-sectoral information.

BUILD CAPACITY IN HEALTH SYSTEMS

Despite the significant advances made in many parts of sub-Saharan Africa in reducing malaria incidence and outbreaks, weak health systems—including understaffed health posts, lack of skilled human capacity, and unreliable supply chain management across the spectrum of services and programs—slow progress toward malaria control goals and targets. Investments need to be made in building the skills and capacity of health workers to understand and address the health risks posed by climate. This includes:

- Training health workers on the links between health and climate change: Many public health workers and leaders are ill-equipped to face the challenges of climate risks and lack an understanding of how health service delivery will need to change. The uptake and use of early warning systems, educational and advisory systems for disseminating clinical guidelines, and even the guidance offered by community health workers will all require building awareness of the risks of climate change and appropriate responses.

- Streamlining supply chain management: Especially in countries where malaria control interventions have been successful, supply chain management will need to be streamlined to guarantee the delivery of commodities and services for remote and mobile populations.
- Promoting research on applied, health services questions: There is a clear lack of service-oriented research to drive regional health service development for climate change, with potentially serious implications for control efforts.

REFINE COUNTRY SELECTION AND STRATEGIC BUDGETING FOR INTERNATIONAL PROGRAMS

The potential impacts of increased temperature on malaria burden are too great to be ignored during country selection and strategic budgeting. New country selection for international programs investing in malaria interventions is complicated and often dictated by many factors, including available funding, national capacity to implement programs, ability to work across agencies, and ability to work with country-specific partners, donors, and stakeholders. While there are many drivers of malaria burden at a national scale, this report demonstrates that increased temperature may contribute to putting large populations at risk of both seasonal and endemic malaria where the burden was previously significantly less. Because of this potential risk, it is important to include projected temperature increases during strategic discussions for country selection in the near and medium term.

The role of temperature in malaria burden in Gabon, for example, where more people are likely to be at risk of both seasonal and endemic malaria by the 2030s due to projected temperature increases, should be considered. Furthermore, temperature projections help to design interventions for populations that may be at risk in the next 10–12 years, potentially preventing large-scale national challenges.

DEVELOP REGIONAL APPROACHES AND PARTNERSHIPS

In addition to country selection, this report has implications for addressing malaria regionally. Some regions of Africa, such as higher elevation areas in Southern and East Africa and parts of Central Africa, will likely have increased burden. Part of the Horn of Africa and West Africa will likely have decreased burden. A regional approach to fighting malaria and regional partnerships and networks may improve strategic targeting and elimination efforts.

OVERVIEW

INTRODUCTION

Climate variability and change present both current and future risks to human health. For example, changes in temperature, precipitation, and extreme weather events alter the geographic range, seasonality, and survival of pathogens and the vectors that transmit them. They also increase human exposure to events such as floods, heat waves, and droughts, and put health infrastructure at risk (e.g., health centers, supply chains) necessary to reduce disease transmission. The World Health Organization¹ has estimated the worldwide health impact of climate change:

- Between the 2030s and 2050s, climate change is expected to cause approximately 250,000 additional *deaths* per year from malnutrition, malaria, diarrhea, and heat stress.
- The direct damage costs to health (i.e., excluding costs in health-determining sectors such as agriculture and water and sanitation) are estimated to be between USD 2 billion to 4 billion/year by the 2030s.

Low-income regions are expected to experience the brunt of the public health impacts of climate change. These regions, in many cases, have higher sensitivity to climate-related hazards (such as extreme rainfall or temperature events) because they have low capacity to respond to and manage those risks. The burden of disease in a given locale, measured as transmission intensity, informs the extent, scale, and timing of malaria interventions. Compounding these issues, knowledge of how, when, and under what circumstances climate change will impact health outcomes is limited, especially for African countries.

OBJECTIVES

The primary objective of this report is to provide health practitioners and development planners with information on the shifting national and regional incidence of malaria in Africa in response to rising temperatures.

¹ World Health Organization. (2018). [Climate change and health factsheet](#).

GEOGRAPHIC SCOPE OF STUDY

To align with USAID programming priorities, models of vector suitability and population exposure are presented at both national and regional scale. The four regions of sub-Saharan Africa analyzed, depicted in Figure 1 are:

- West Africa
- East Africa
- Central Africa
- Southern Africa

Figure 1: Geographic scope of the analysis



METHODS

We mapped areas of malaria suitability in a model combining temperature change projections and current knowledge about the life cycles of malaria-carrying mosquitoes and the malaria parasite. We projected malaria suitability across three time periods:

2030s (representing the period between 2020 and 2039), 2050s (representing the period between 2040 and 2059), and 2080s (representing the period between 2070 and 2099).

The analysis of vector suitability considering future temperature projections is based on an empirical modeling methodology (see box below). The method of Ryan et al. (2015) is extended, applying the model from (Mordecai et al. 2013) to climate model layers (described in Input Data below). All calculations are conducted in R [3.5.0], using the “raster,” “rgdal,” “sp,” and “maptools” functions, and mapped output is produced in ArcGIS (Version 10.5.1).

INPUT DATA

- A multimodel ensemble representing future mean temperature is compiled from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive, downscaled using a Change Factor (CF) approach and sourced from Navarro-Racines et al. (2015). The ensemble allows exploration of a range of climate projections under two Representative Concentration Pathways (RCPs)—RCP 4.5 and RCP 8.5—for the three future time periods (see box).

- Countries of Africa are derived from a shapefile of the database of Global Administrative Areas (GADM), and regions are described in the shapefile.
- To exclude arid areas that preclude *Anopheles* development, the Moderate-Resolution Imaging Spectroradiometer (MODIS)-derived normalized difference vegetation index (NDVI) values for 2016 and 2017 are used to create an “aridity mask,” as described below.
- Population data used as input to the calculations are derived from the Gridded Population of the World, Version 4.11 (Center For International Earth Science Information Network-CIESIN-Columbia University 2016). Baseline calculations use 2015 data, while projected populations are extracted from the 2020 layers as explained in the methodology below.

EXAMINING IMPACTS FROM FUTURE TEMPERATURE RISE USING SCENARIOS

To explore how the planet might change in the future, considering emissions, climate, environmental change, and vulnerability, the Intergovernmental Panel on Climate Change uses scenarios, termed Representative Concentration Pathways (RCPs).

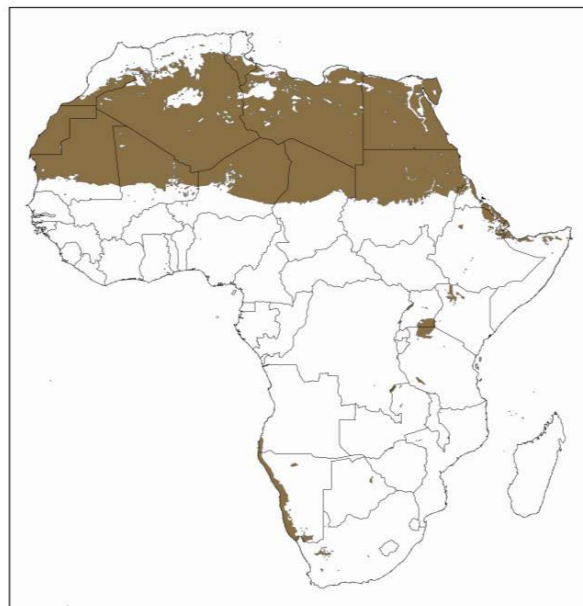
These include: RCP 8.5, RCP 6, RCP 4.5, and RCP 2.6. The numbers refer to radiative forcing, a measure of the impact of greenhouse gases in the atmosphere on the Earth's normal energy balance.

This information is translated through models of climate dynamics and used to project increases in temperature because of increased greenhouse gas concentrations in the atmosphere.

MODEL DESCRIPTION

Malaria transmission suitability model. Using the mechanistic model mentioned above (Mordecai et al. 2013, Mordecai et al. 2017), R_0 , the metric for transmission suitability, scaled from 0 to 1, is described in quantiles. The top quantile (top 25 percent) of the curve is selected to represent the range of temperature in which transmission suitability is expected. This conservative measure of the overall temperature curve is used because it was previously shown to correspond visually to existing maps of ongoing transmission, under current temperatures (Ryan et al. 2015). Using this “most suitable” quantile, this temperature range is incorporated into projections of suitability, as described in the following sections.

Figure 2: Areas masked out of the analysis due to aridity calculations, and including large bodies of water



Aridity mask: To exclude areas that are too arid for the *Anopheles* mosquito's life cycle, the methods of Ryan et al. (2015) are used to create a geographic or "aridity" mask. Monthly NDVI values are derived from postprocessed MODIS data (Suzuki et al. 2006), and month-to-month thresholding is calculated. That is, if the NDVI values for two consecutive months fall below 0.125, an aridity boundary is crossed (Suzuki et al. 2006), indicating that the area (pixel) is too dry for malaria transmission (Figure 2).

DEFINING SUITABILITY

We modified the Mapping Malaria Risk in Africa (MARA) definitions of malaria suitability to better illustrate the impact of changing climate and to provide information that decision-makers can use to carry out control and/or intervention activities. Our definitions specify the duration in months per year of malaria transmission suitability:

- **Endemic:** 10–12 months
- **Seasonal:** 7–9 months
- **Moderate:** 4–6 months
- **Marginal:** 1–3 months

The suitability measure is derived from temperature response curves for the mosquito species *Anopheles gambiae* and the malaria pathogen (*Plasmodium falciparum*). The report assesses the ways in which suitability will shift as temperatures rise under two climate scenarios—moderate temperature increase (RCP 4.5) and higher-temperature increase (RCP 8.5)—at three time periods (2030s, 2050s, and 2080s).

1. Unsuitable to endemic
2. Unsuitable to seasonal
3. Seasonal to endemic
4. Moderately or marginally suitable to endemic
5. Moderately or marginally suitable to seasonal
6. Endemic to seasonal

We limited the study to these six states of change because in our view they are among the most relevant of the over 200 possible states of change for the four levels of malaria suitability (plus unsuitable), three time periods, and two climate scenarios.

OVERVIEW OF EMPIRICAL MODELS

A fundamental underpinning of modeling the response of vector-borne diseases to climate and ecology is the choice of model process. Previous approaches, such as that of the Malaria Atlas Project (MAP) and the Mapping Malaria Risk in Africa (MARA) project, have used an essentially top-down approach, where empirical data collected on the ground are matched to local climate conditions, and suitability established via geostatistical methods.

In contrast, the modeling approach used in this analysis is mechanistic and “bottom-up,” where the life history of mosquitoes and pathogens, and their responses to temperature, are explicitly quantified based on empirical, laboratory-based data and incorporated into the model to predict where suitability for transmission is likely to occur. A mechanistic model, built independently of case outcome data, allows for validation with empirical, field-collected data, and obviates the bias of modeling data while an intervention is ongoing, as is inevitably the case with previous approaches. It also lacks the spatial bias that may arise from various assumptions, such as clinic locations substituted for households, or household locations substituted for job sites.

Anopheles mosquitoes (i.e., malaria-transmitting mosquitoes) require a certain level of moisture in their environment to breed and complete their life cycle. Humidity or moisture is thus another component in the climate–transmission relationship. While several models use rainfall as a predictor for malaria occurrence (Thompson et al. 2005, Grover-Kopec et al. 2005, Pascual et al. 2008, Craig et al. 1999), it is complicated to generalize how precipitation measures, such as monthly rainfall totals, cumulative rainfall, or relative humidity, manifest as breeding habitat for mosquitoes at large scales. Precipitation may not be a good indicator of standing water, and in a world of increasingly extreme precipitation events, the difference between a month’s rainfall occurring in a single day versus gradual accumulation over that month becomes more relevant. Mosquito habitat can wash away, “flushing” away eggs and disrupting the life cycle. In addition, much of the world is subject to agricultural irrigation, redirecting precipitation in nonlinear ways at local level, or even creating piped water environments in the absence of precipitation.

To generalize habitat suitability for mosquito breeding, a remotely sensed proxy is used: the normalized difference vegetation index (NDVI), which measures the photosynthetic activity of growing plant matter. The NDVI is thus a useful descriptor of the type of habitat conducive to *Anopheles* breeding. The threshold of “too dry” is based on work by Suzuki et al. (2006) to exclude locations where the NDVI drops below a critical minimum level for two months of the year, thereby cutting off breeding and the transmission cycle.

RESULTS AND DISCUSSION

It is generally accepted that climate change, particularly increased temperatures and changing rainfall patterns (Thomson et al. 2005), threatens to change the nature of malaria exposure across sub-Saharan Africa. An understanding of changing malaria exposure at regional and national scale is limited, although such knowledge is critical to designing malaria surveillance and responses.

BASELINE AND OVERVIEW OF PROJECTED CHANGES

CURRENT DISTRIBUTION OF MALARIA

The modeled current distribution of areas with endemic or seasonal malaria suitability aligns well with areas where malaria currently occurs (Figure 3). For simplicity, the results are presented in a selection of maps and charts to illustrate the projected changes in suitability and number of people exposed.

FUTURE CLIMATE PROJECTIONS

Higher temperatures are projected under all models and time periods evaluated for the continent. The evidence on projected increases in temperature of relevance to the modeled outcomes by region is synthesized in Table 1.

Table 1. Average annual temperature increases (°C) from baseline (1960–1990) by region, RCP, and time period, referenced in the empirical model results presented here

Region	2030s		2050s		2080s	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
West Africa	1.32	1.57	2.29	2.32	2.84	4.5
East Africa	1.32	1.63	1.90	2.32	2.96	4.38
Central Africa	1.10	1.42	1.63	2.07	2.69	4.04
Southern Africa	0.94	1.28	1.33	2.01	2.51	4.08

Note: Average projected regional changes in mean temperatures calculated within regional boundaries.

CHANGES IN OVERALL MALARIA SUITABILITY

The geographic and temporal shifts of future suitability of areas for malaria-transmitting *Anopheles* mosquitoes is closely tied to expected temperature changes under both RCP 4.5 and RCP 8.5 (Figure 4). Note that areas in white in this figure do not necessarily represent a complete elimination in months of suitability of malaria under endemic or seasonal conditions; in fact, white areas could represent areas that continue to be either moderately or marginally suitable. These scenarios indicate that as temperatures rise, important changes are expected in *Anopheles* transmission suitability:

- By the 2050s, large areas of coastal West Africa and the Horn of Africa are expected to exceed mosquitoes' thermal tolerance, with suitability substantially reduced to a few months.
- At the same time (2030s–2050s), rising temperatures will likely increase the southern range of seasonal suitability for *Anopheles* mosquitoes into Southern and Central Africa.
- By the 2050s, as temperatures continue to rise, both endemic and seasonal zones will likely continue to exhibit an eastward shift. Under the worst-case scenario (RCP 8.5), thermal threshold is exceeded, and suitability will likely be eliminated across Central Africa.
- By the end of the century (2080s), concentrated areas of endemism will likely emerge in previously unsuitable or marginally suitable areas, namely the highlands of East Africa and Southern Africa.

Figure 3. Current extent of areas classified as endemic (10–12 months of suitability) and seasonal (7–9 months of suitability)

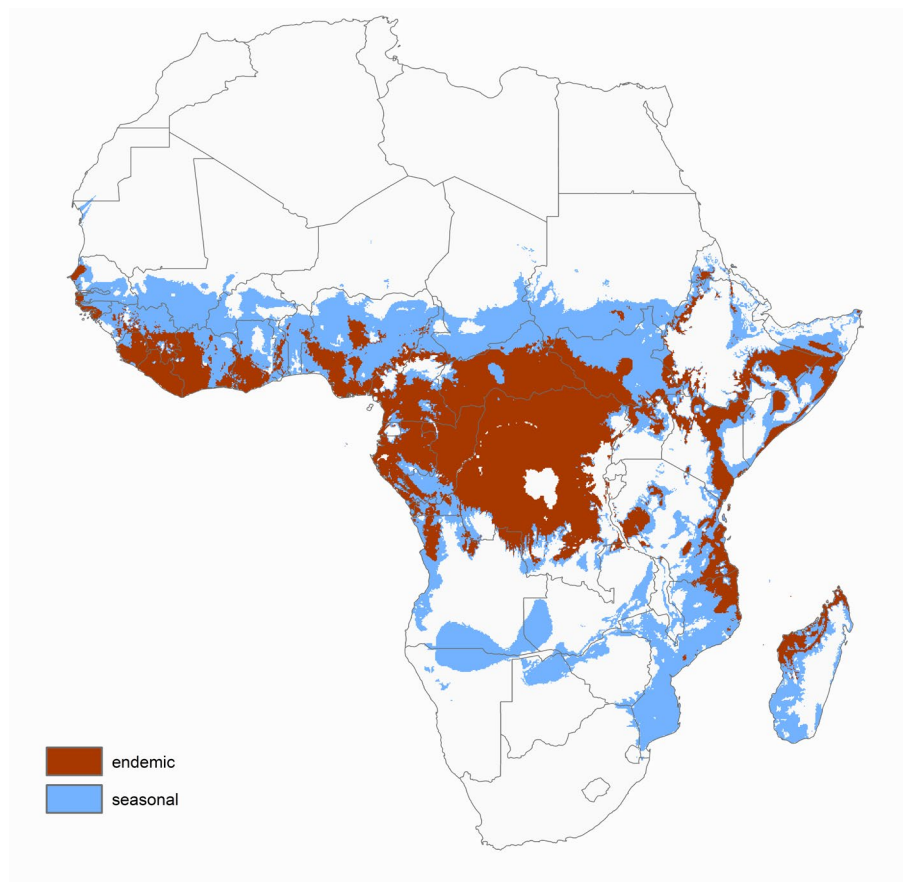
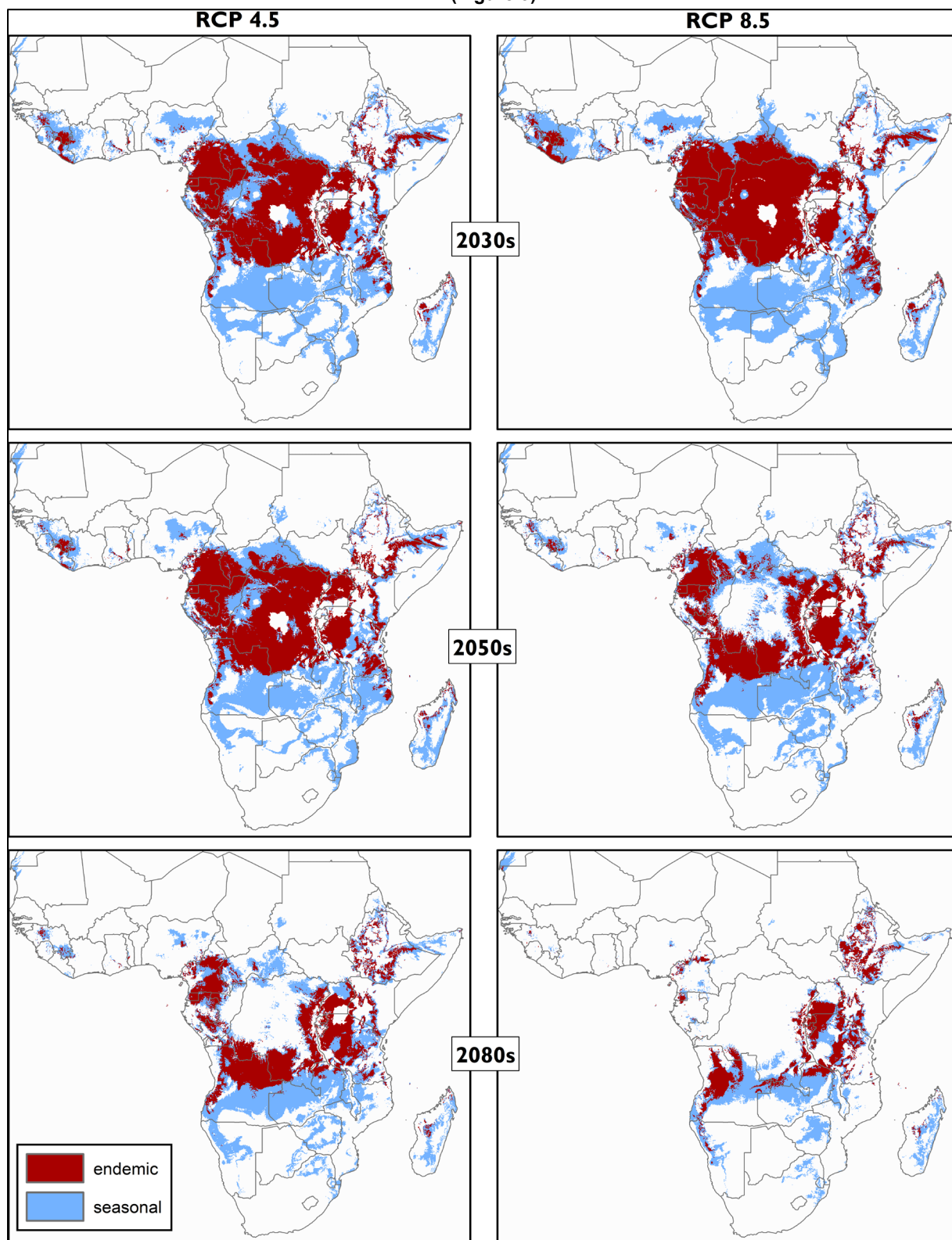


Figure 4: Projected extent of areas classified as endemic (10–12 months of suitability) and seasonal (7–9 months of suitability) for malaria under three time periods and two RCPs relative to the 1960-1900 baseline (Figure 3)



These changes in the geographic range of malaria suitability, broadly consistent across both scenarios of future climate, suggest that the number of people exposed to conditions of suitability will likely both increase and decrease. Nevertheless, the maps also show that there is significant spatial variability.

Different temperature projections can lead to significant changes in the numbers of people exposed to malaria risk. Some general trends in the number of people affected include:

- Approximately 16 to 18 million people, currently living in areas with no suitability will be at risk from endemic exposure to transmission in East Africa under both best case (RCP 4.5) and worst-case scenario (RCP 8.5) by the 2030s.
- Approximately 47 to 58 million people will see reduced endemic risk (10–12 months) but will still experience marginal to moderate risk (1–6 months) in West Africa due to temperatures exceeding thermal thresholds for mosquitoes. The net change in numbers of people at any risk of malaria transmission (those moving from endemic, seasonal, or no suitability to marginal/moderate malaria exposure) in West Africa will be an increase of approximately 65 million people by the 2030s under the best-case scenario (RCP 4.5).

MALARIA BURDEN BY THE 2030S: NEAR-TERM RESULTS AND WHAT THEY COULD MEAN FOR DECISION-MAKING

This analysis illustrates the likely shift in malaria suitability under increased temperatures caused by climate change that puts lives at risk. This information improves our understanding of the likely change in malaria seasonality across the continent, with important implications for malaria management and programming.

Key findings:

- As temperatures rise, **new challenges to prevent and treat malaria** across the continent will emerge.
- By 2030, increased temperatures will likely put **more people across Africa at risk** from exposure to malaria, while at the same time reducing the risk to others.
- Improved understanding of the influence of temperature on malaria can lead to **better planning and response**, including detailed geographic targeting and seasonal alignment with interventions, which could limit increases in malaria transmission.

New areas of malaria suitability

Overview: Malaria outbreaks where people have little or no immunity to the disease can often lead to epidemic “flares”, especially among vulnerable groups such as pregnant women and children.

Risk: These new areas of suitability will result in roughly 22-36 million **additional** people exposed to endemic and seasonal malaria risk by the 2030s

Opportunity: Targeted and concentrated surveillance at the edge of malaria’s range offers the opportunity to control potential epidemic outbreaks as they happen and can reduce the risk of novel outbreaks.

Areas where the malaria season will be extended

Overview: This category identifies regions where targeted interventions could potentially include an assessment of how climate will alter risk profiles for malaria in the future.

Risk: More people will be exposed for a longer period to malaria transmitting mosquitos.

Opportunity: Malaria response programs will need to be extended, increasing resource needs (e.g. staff time, medicines) as well as costs, and requiring an extended investment pipeline.

PROJECTED CHANGES IN DETAIL

Shifts in both the areas and populations exposed to malaria risks will require a change in the portfolio of responses to address those risks. Many countries with a high burden of malaria have weak surveillance systems and are not able to assess disease distribution and trends, making it difficult to optimize responses and respond to outbreaks. The following analysis offers insights for programming decisions by exploring six scenarios of changing suitability. Not all potential scenarios of change were evaluated; rather, these scenarios highlight the changing profile of risk across the region but could be expanded to include other shifts, such as from endemic or seasonal to marginal or moderate suitability. These will be evaluated in subsequent studies. The six scenarios of changing suitability are:

New areas of malaria suitability

1. Where and when are new areas of endemic suitability going to emerge where malaria was previously unsuitable? How many people are at risk from this change?
2. Where and when are new areas of seasonal suitability going to emerge where malaria was previously unsuitable? How many people are at risk from this change?

Areas where the malaria season will be extended

3. Where and when will seasonal areas become endemic? How many people are at risk from this change?
4. Where and when will moderately or marginally suitable areas become endemic? How many people are at risk from this change?
5. Where and when will moderately or marginally suitable areas become seasonal? How many people are at risk from this change?

Areas where the malaria season will be shortened

6. Where and when will endemic areas become seasonal? How many people are affected by this change?

The responses to the questions are translated into projected temperature changes. A quantitative analysis of responses to each set of questions follows.

NEW AREAS OF MALARIA SUITABILITY

Malaria outbreaks that occur where people have little or no immunity to the disease can often lead to epidemic conditions, especially among vulnerable groups such as pregnant women, children, and the elderly. These research questions aim to identify such “hotspots.” These areas could see epidemic “flares” as climate conditions affect vector survival and reproduction.

Research Question 1: Where and when are new areas of endemic suitability going to emerge where malaria was previously unsuitable? How many people are at risk from this change?

Figure 5 shows areas previously unsuitable for malaria that will shift to endemic conditions (10–12 months per year of malaria suitability) for the three future time periods and two climate scenarios evaluated. Essentially, these areas were too cold to allow the mosquito/parasite to complete the transmission cycle. Hotspots of endemic suitability begin to emerge in the East African highlands, the Lake Victoria region, northern Angola, and southern DRC, becoming more pronounced in the 2050s and 2080s. In these new areas of suitability, approximately 34 to 40 million additional people will be exposed to endemic risk by the 2030s in East Africa alone, under both RCP 4.5 and RCP 8.5 (Figure 6).

With respect to the current number of people living in conditions of endemic suitability today, the largest changes will be seen in Rwanda, where approximately 76,000 to 1 million people, currently living outside of any malaria suitability will enter conditions of endemic suitability by the 2030s. In Uganda, approximately 4 to 6 million people will be experiencing this change, from no malaria suitability to endemic suitability by the 2030s under both climate scenarios, relative to the current 4 million currently living under conditions of endemic suitability. The number of people at risk from endemic suitability will more than double.

Research Question 2: Where and when are new areas of seasonal suitability going to emerge where malaria was previously unsuitable? How many people are at risk from this change?

Figure 7 shows where areas previously unsuitable for malaria will shift to conditions of seasonal exposure (7–9 months per year of suitability). Concentrated hotspots of seasonal suitability begin to emerge in central Angola, northwestern Zambia, northern Tanzania, and the southern coast and northern region of Mozambique by the 2030s. These hotspots will either continue to concentrate or will move both northward and southward into the highlands of Ethiopia and Southern Africa approaching the 2050s and 2080s.

These new areas of suitability will put approximately 12 to 18 million and 14 to 34 million people at risk of exposure to seasonal conditions by the 2030s and 2050s, respectively. The most marked increases will be in East Africa, where approximately 10 to 15 million additional people will enter conditions of seasonal risk by the 2030s (Figure 8).

These new areas of suitability will put approximately 12 to 18 million or 14 to 34 million people at risk of exposure to seasonal conditions by the 2030s, and the 2050s, respectively, with the most marked increases seen in East Africa, where approximately 10 to 15 million additional people will enter into conditions of seasonal risk by the 2030s (Figure 8).

Figure 5. Areas that are not suitable under current climate for malaria but will become endemically suitable under a changing climate across both RCP 4.5 and RCP 8.5 by the 2030s, 2050s, and 2080s

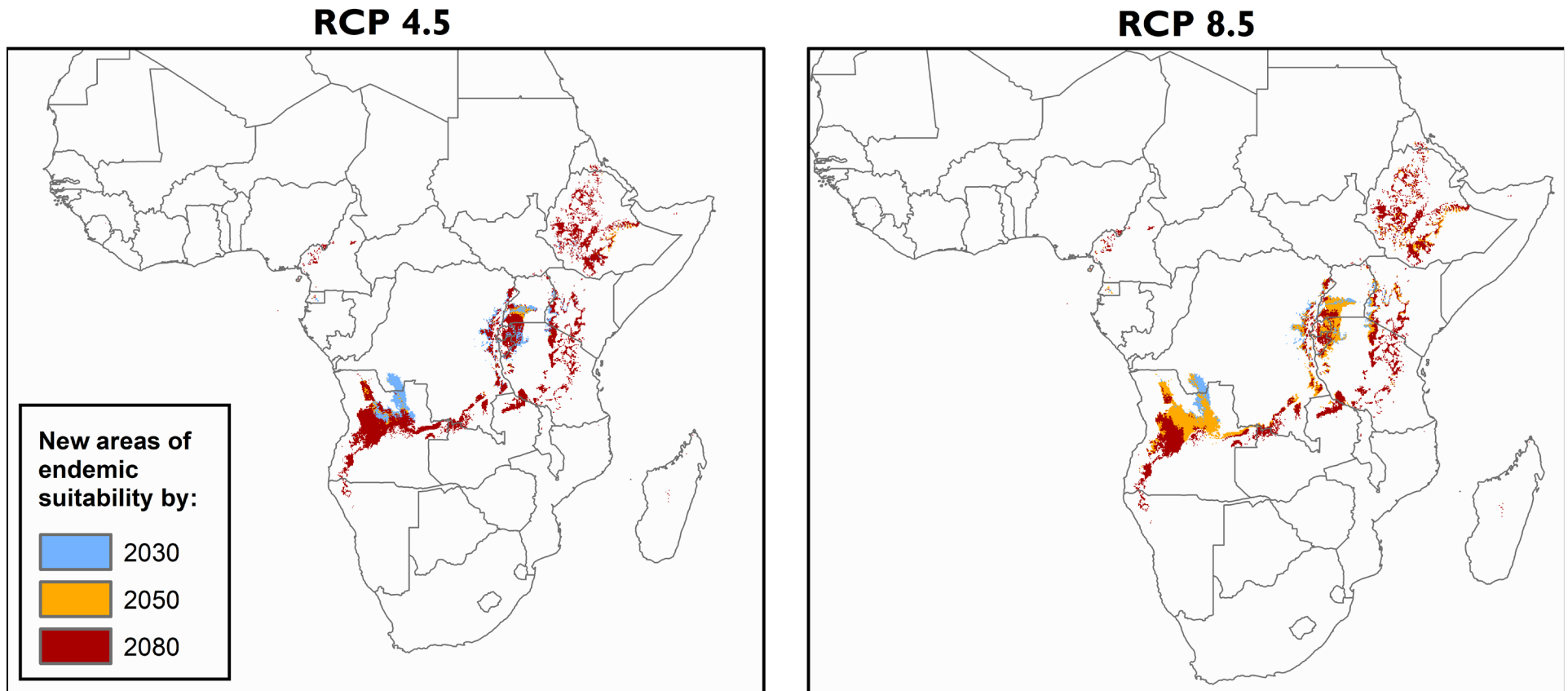
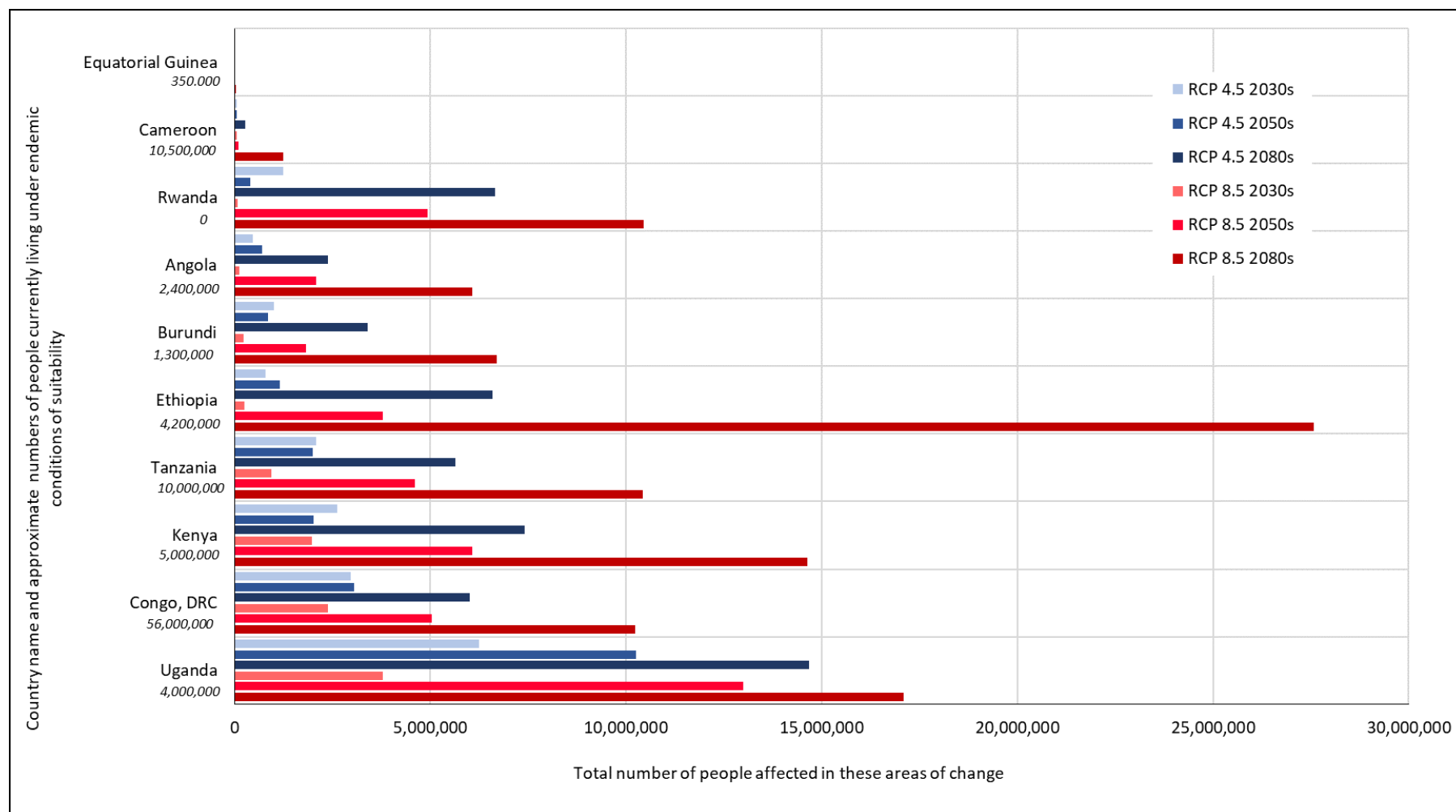


Figure 6. Additional number of people that could be at risk in areas that will become newly endemically suitable but where previously unsuitable by the 2030s, 2050s, and 2080s under both climate futures evaluated, 10–12 months per year)



Note: Top 10 countries in terms of numbers of people affected by the 2030s and RCP 4.5 are shown here. Approximate numbers of people living in endemic conditions of suitability current are listed in italics below the country name on the vertical axis, for comparative purposes.

Figure 7. Areas that are not suitable under current climate for malaria but will become seasonally suitable under a changing climate across both RCP 4.5 and RCP 8.5 by the 2030s, 2050s, and 2080s

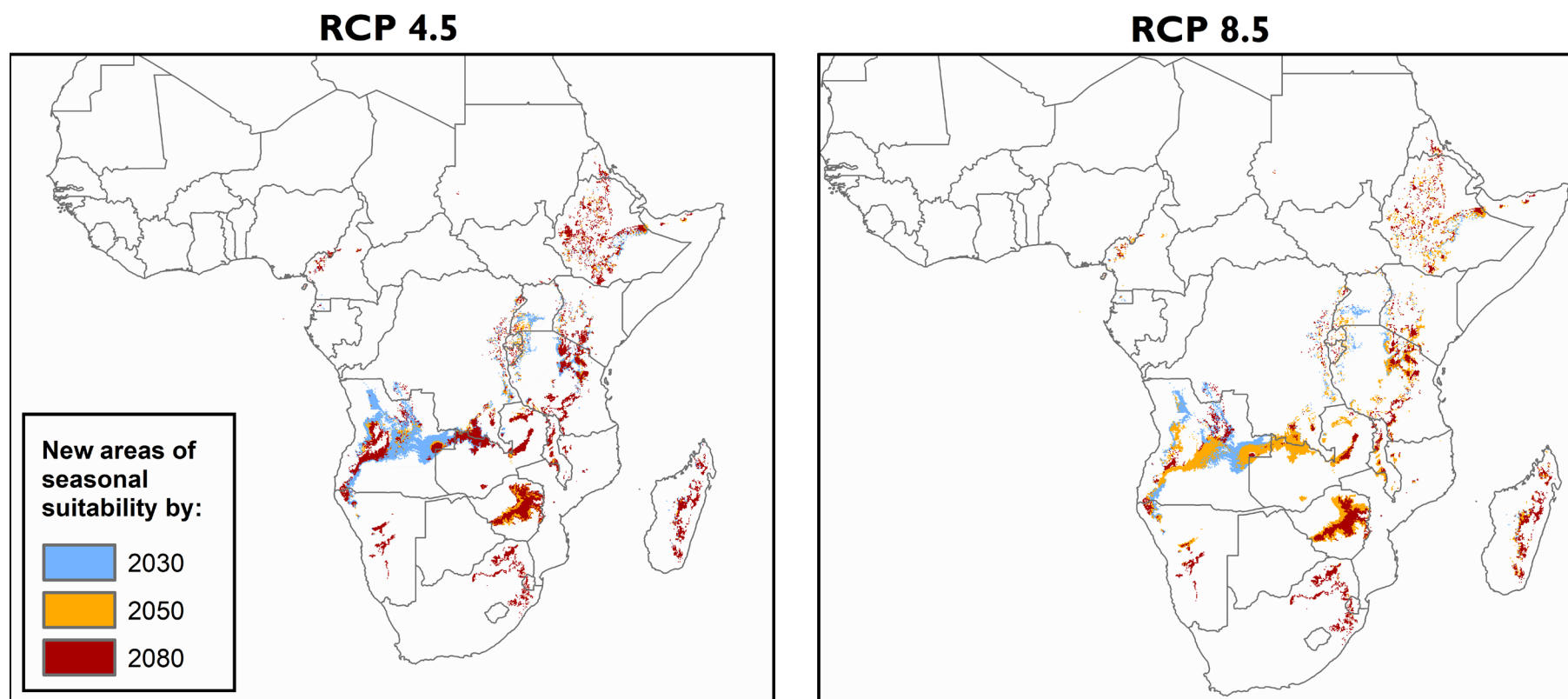
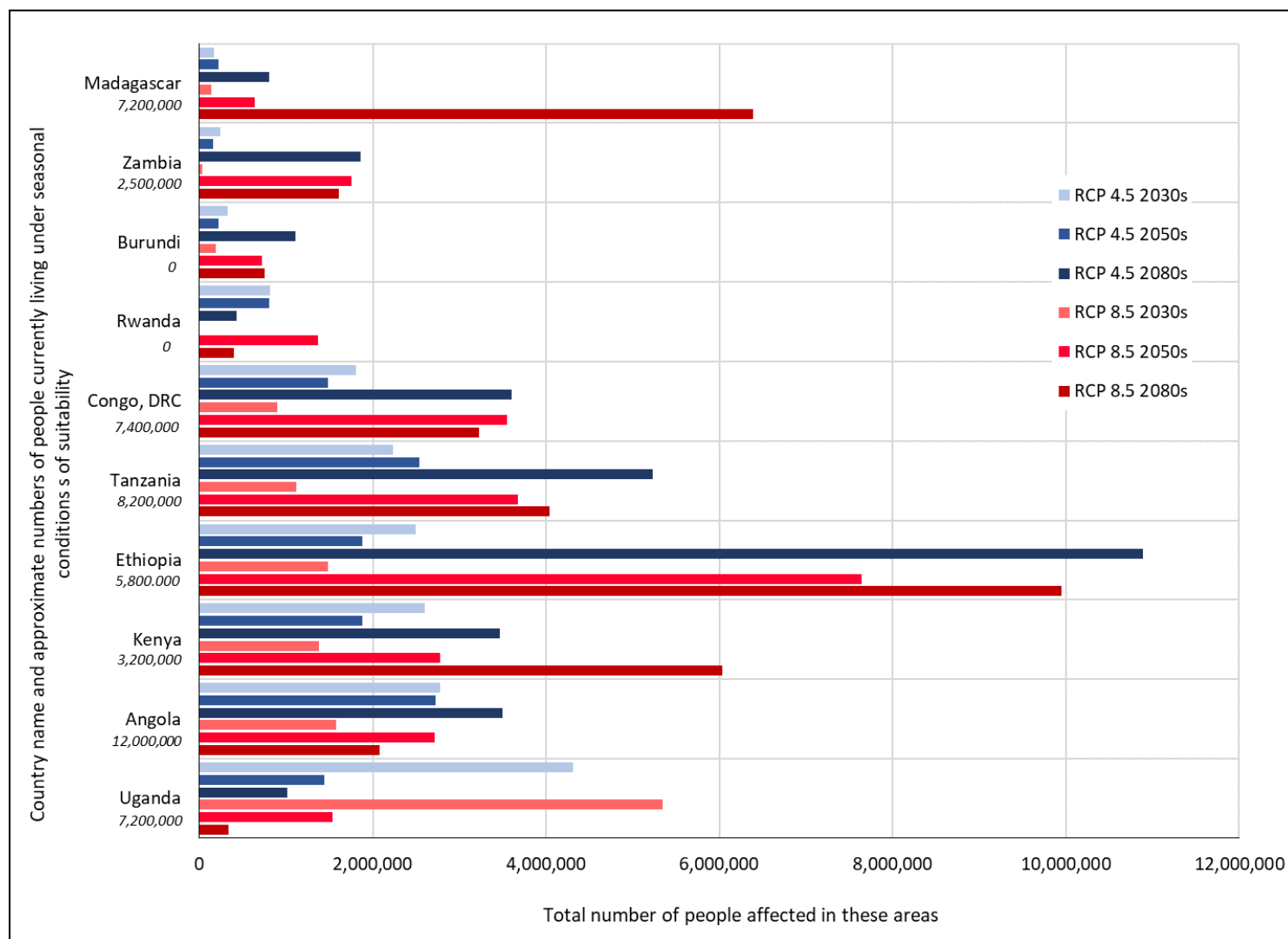


Figure 8. Additional numbers of people that could be at risk in areas that will become newly suitable for seasonal malaria but where previously unsuitable by the 2030s, 2050s, and 2080s under both climate futures evaluated.



Note: Top 10 countries in terms of numbers of people affected by the 2030s and RCP 4.5 are shown here. Approximate numbers of people living in seasonal conditions of suitability current are listed in italics below the country name on the vertical axis, for comparative purposes.

EXTENSION OF THE MALARIA SEASON

In areas where people have acquired immunity due to prolonged malaria exposure, outbreaks of malaria trigger interventions such as vector control and case management to prevent or reduce transmission. The goal is to pinpoint areas where elimination and elimination targets need to be revisited to consider the effect of climate on malaria risk profiles.

Research Question 3: Where and when will seasonal areas become endemic? How many people are at risk from this change?

An increase in the number of months where conditions are suitable for mosquito survival (Figure 9) will require extended responses, increasing resource needs (e.g., staff time, medicines) as well as costs. A hotspot for the 2030s is East Africa, which will see an increase of approximately 29 to 30 million people at risk. This is reflected in the changes projected for Uganda, for example, where an additional approximately 4 to 8 million people shift from areas of seasonal to endemic risk (Figure 10).

Research Question 4: Where and when will moderately or marginally suitable areas become endemic? How many people are at risk from this change?

Given the strong empirical relationship between vector survival and temperature, and provided there is enough moisture for vector reproduction, as temperatures rise, exposure to malaria transmission is expected to increase in previously moderately or marginally suitable regions, such as the higher elevations of Southern and East Africa. Areas likely to be impacted by these changes include northern Angola, southern DRC, western Tanzania, and central Uganda by the 2030s. By the 2050s impacted areas may extend into western Angola, the upper Zambezi River Basin, and northeastern Zambia, as well as becoming more concentrated along the East African highlands (Figure 11). These changes could affect approximately 33 to 37 million people in East Africa alone as early as the 2030s, and in terms of the current burden of endemic disease, could add 6 to 11 million people to those currently living under endemic conditions (currently approximately 2 million) in Tanzania alone, across all future time periods (Figure 12).

Research Question 5: Where and when will moderately or marginally suitable areas become seasonal? How many people are at risk from this change?

Areas that are currently moderately or marginally suitable for *Anopheles* transmission but will shift to seasonally suitable are found mainly in East Africa. This includes large portions of Tanzania, Uganda, and Northern Mozambique (Figure 13). These changes will put approximately 27 to 29 million people at increased risk from transmission under the best-case scenario (RCP 4.5) by the 2030s, adding an additional approximately 9 to 12 million people to those currently living in seasonal conditions of risk in Zambia alone across all time periods and scenarios (Figure 14).

Figure 9. Areas that are currently considered seasonally suitable for malaria but will change to endemically suitable under a changing climate across both RCP 4.5 and RCP 8.5 by the 2030s, 2050s, and 2080s

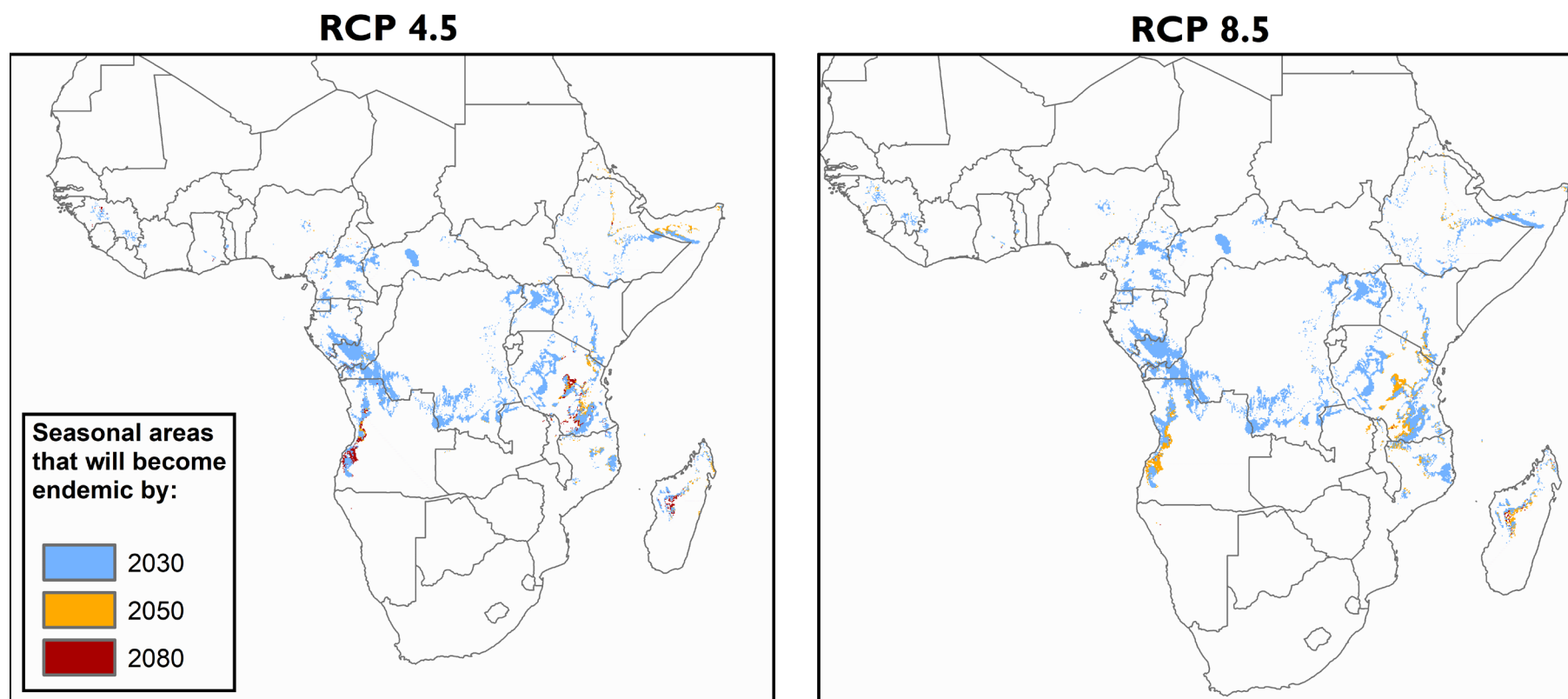
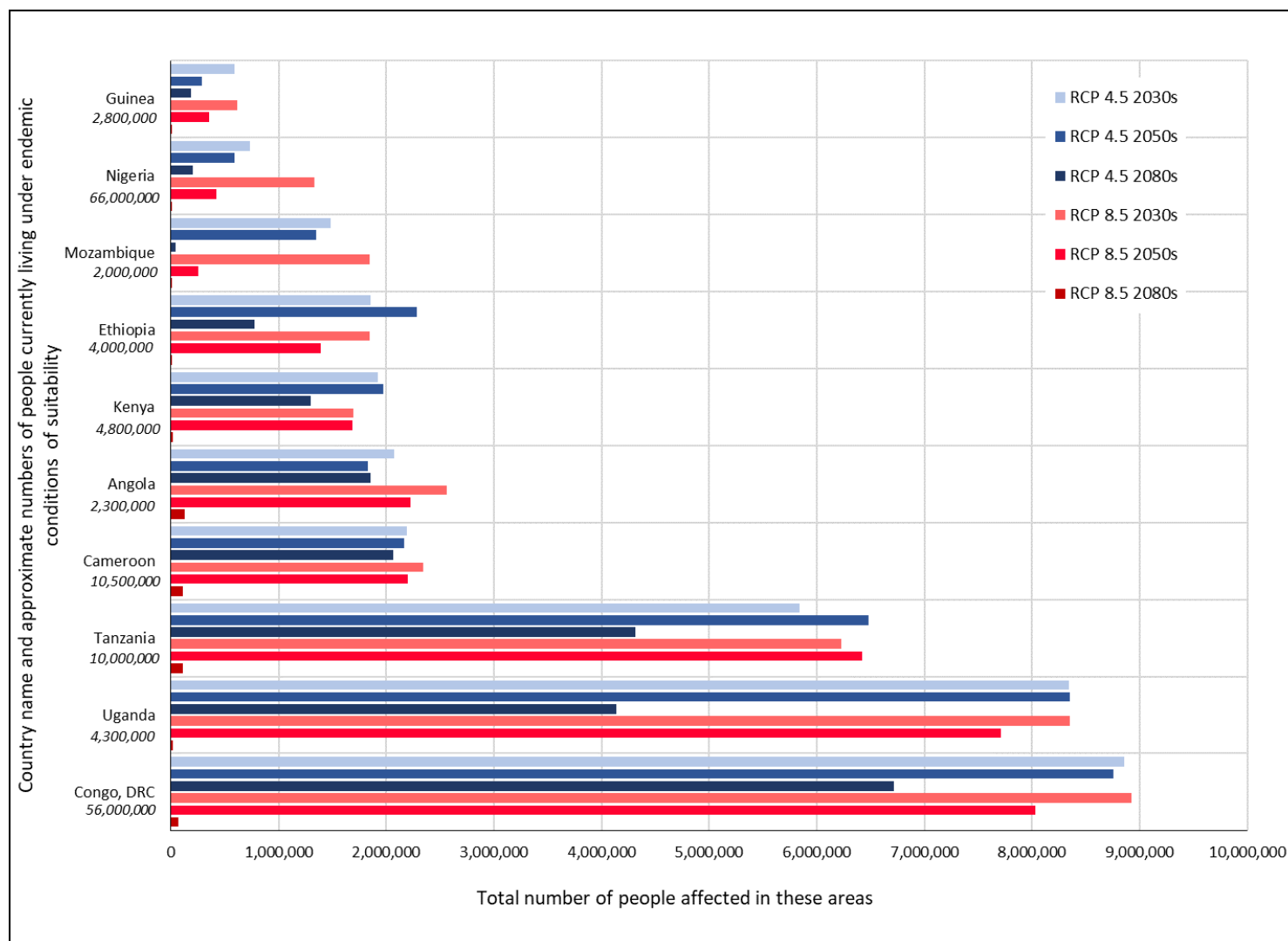


Figure 10. Number of people currently living under seasonal conditions of suitability that are projected to live under conditions of endemic suitability by the 2030s, 2050s, and 2080s under both climate futures evaluated (10-12 months per year)



Note: Top 10 countries in terms of numbers of people affected by the 2030s and RCP 4.5 are shown here. Approximate numbers of people living in seasonal conditions of suitability current are listed in italics below the country name on the vertical axis, for comparative purposes.

Figure 11. Areas that are currently considered marginally or moderately suitable for malaria but will change to endemically suitable under a changing climate across both RCP 4.5 and RCP 8.5 by 2030s, 2050s, and 2080s

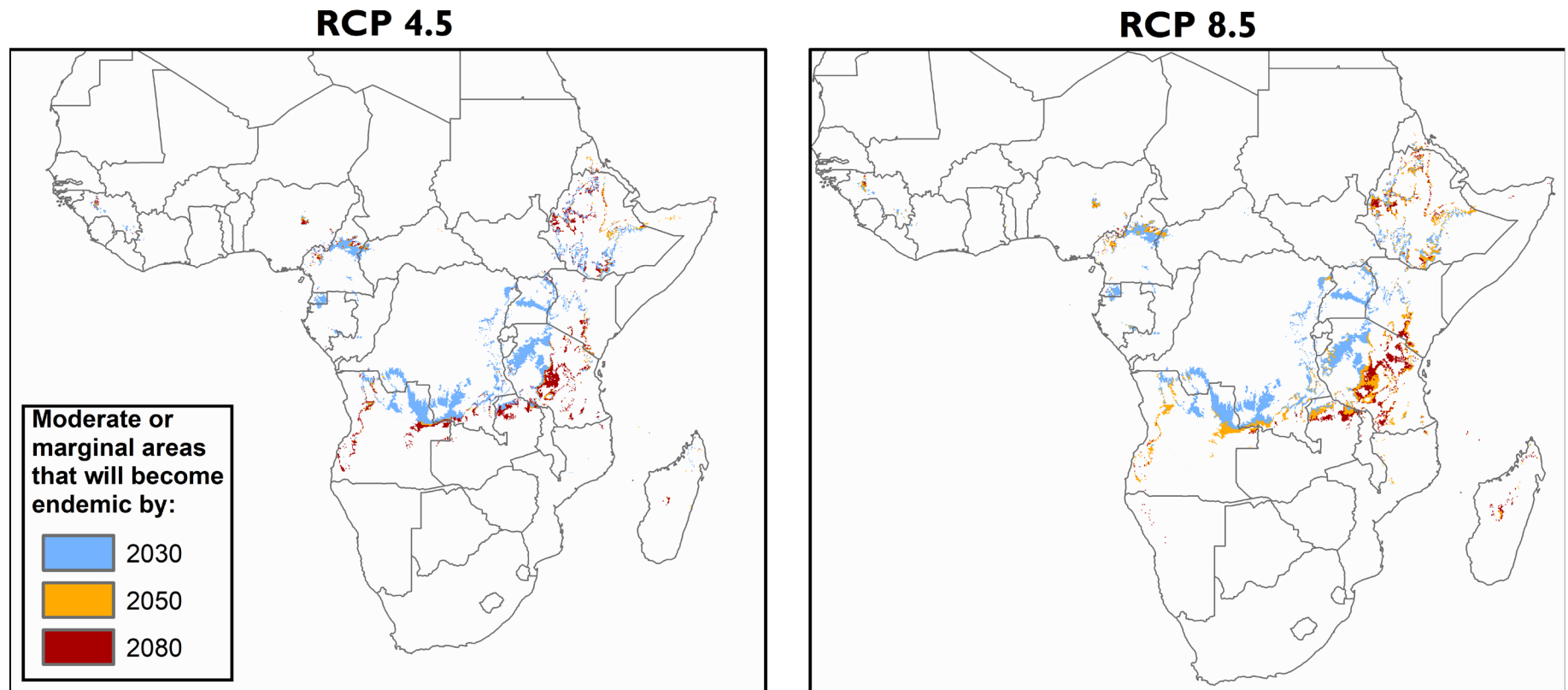
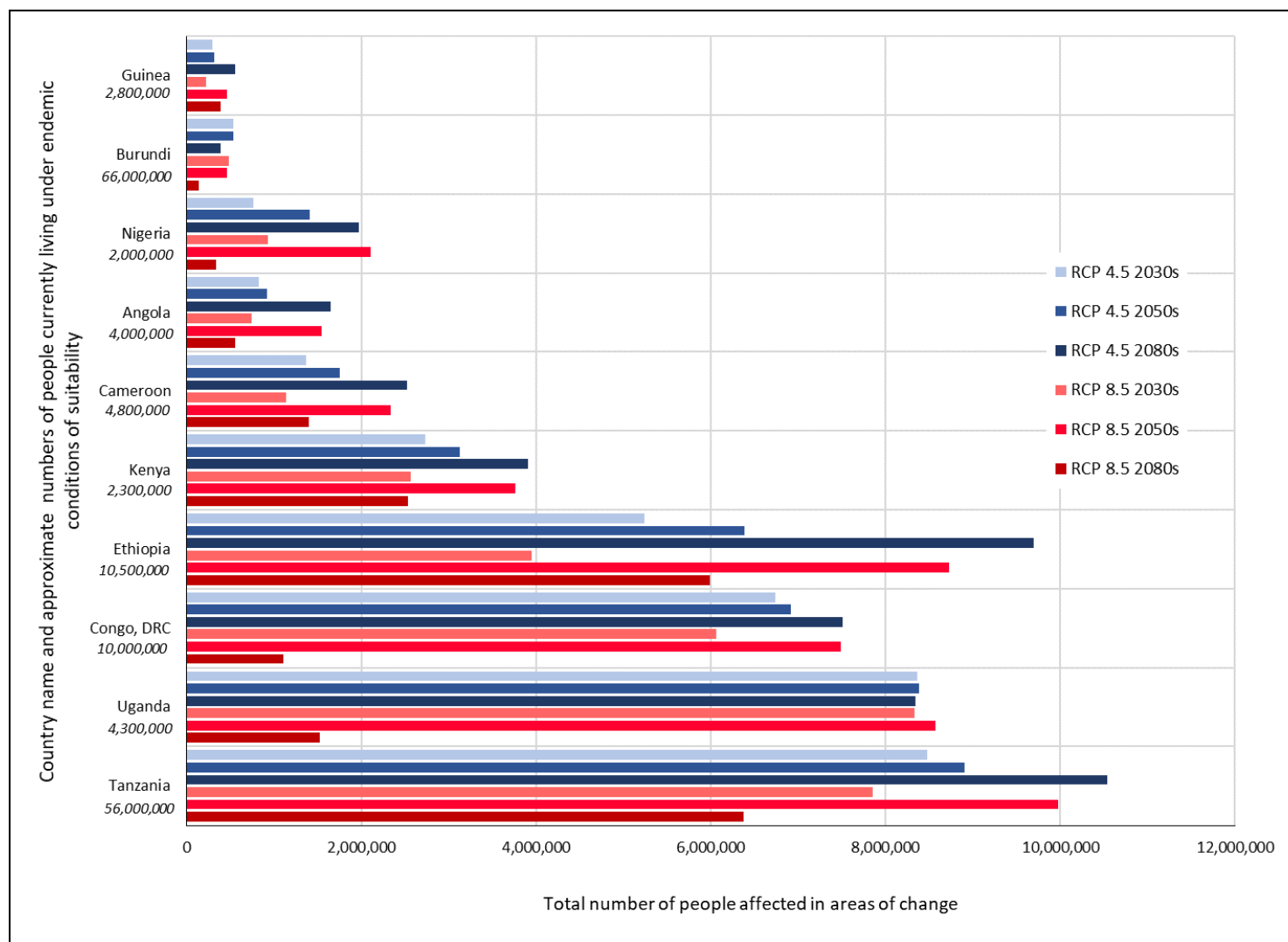


Figure 12. Number of people at risk in areas shifting from marginally or moderately suitable to endemically suitable for malaria under a changing climate by the 2030s, 2050s, and 2080s under both climate scenarios (RCP 4.5 and RCP 8.5)



Note: Top 10 countries in terms of numbers of people affected by the 2030s and RCP 4.5 are shown here. Approximate numbers of people living in seasonal conditions of suitability current are listed in italics below the country name on the vertical axis, for comparative purposes.

Figure 13. Areas that are currently considered marginally or moderately suitable for malaria but will change to seasonally suitable under a changing climate across both RCP 4.5 and RCP 8.5 by the 2030s, 2050s, and 2080s

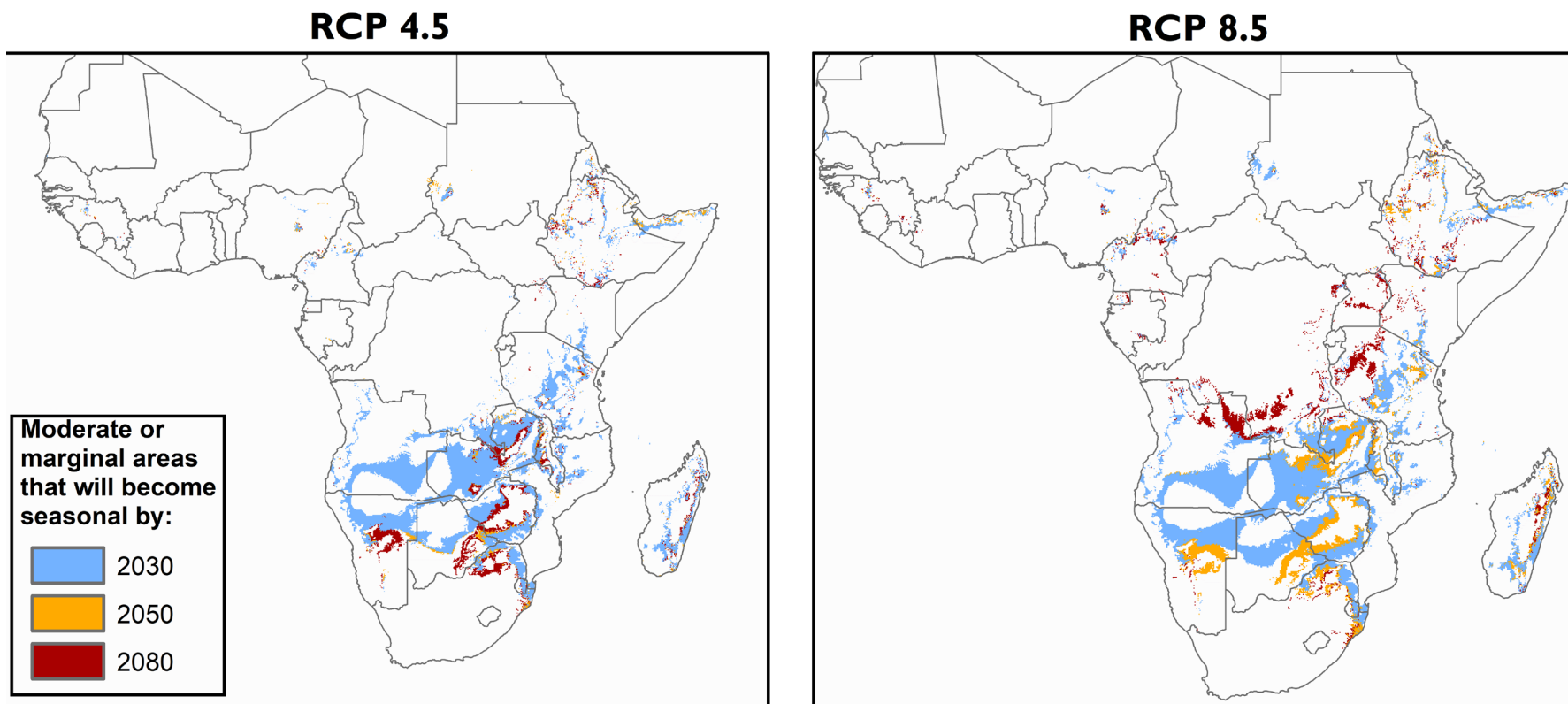
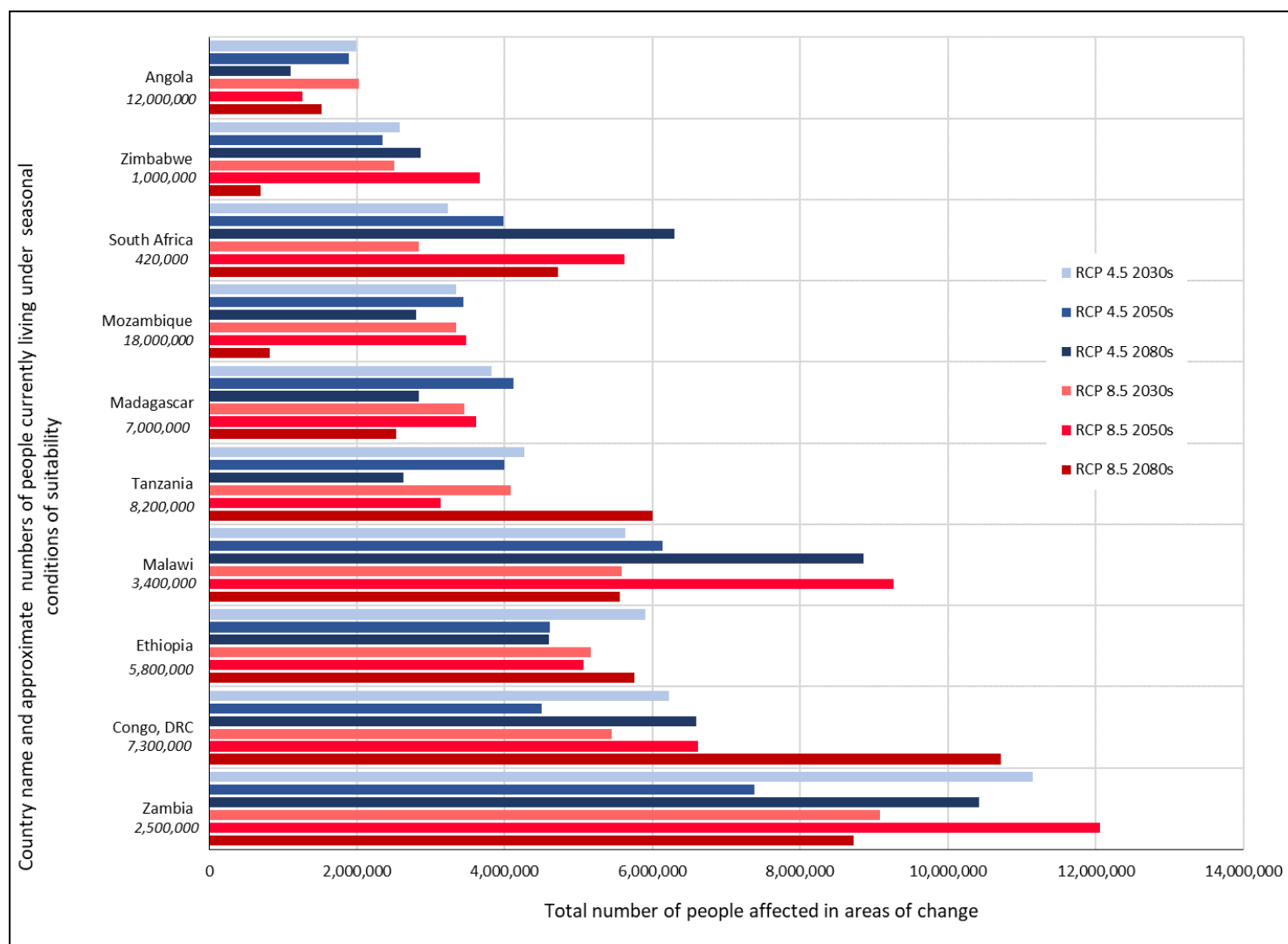


Figure 14. Number of people living in moderate or marginal conditions and will add to the numbers living under seasonal conditions of suitability by the 2030s, 2050s, and 2080s under both climate scenarios evaluated, relative to the current number of people living under seasonal suitability (7-9 months per year)



Note: Top 10 countries in terms of numbers of people affected by the 2030s and RCP 4.5 are shown here. Approximate numbers of people living in seasonal conditions of suitability current are listed in italics below the country name on the vertical axis, for comparative purposes

SHORTENING OF THE MALARIA SEASON

The strong seasonal cycle of malaria across Africa is related to climate and weather conditions. Other factors, such as changing agricultural activities which alter food availability, can affect malaria's seasonal cycle. Thus, during some periods of the year, climate conditions are not conducive to spread of the disease. A key opportunity lies in the possibility of climate change reducing the period during which the *Anopheles* mosquito thrives and transmits malaria. This may ultimately present an opportunity to alter control efforts and/or shift resources to other more critical areas.

Research Question 6: Where and when will endemic areas become seasonal? How many people will be affected by this change?

- Where the number of months of suitability for *Anopheles* survival decreases, opportunities will emerge to reduce the cost of interventions or eradicate malaria. As shown in Figure 15, significant changes will be seen in West Africa, where approximately 47 to 58 million people will see reduced endemic risk due to temperatures exceeding the thermal thresholds for mosquitoes. But these areas will still experience marginal to moderate risk. The net change in numbers of people at any risk of malaria transmission (those moving to marginal/moderate malaria exposure) will increase by approximately 65 million people in West Africa alone by the 2030s under the best-case scenario (RCP 4.5). In Nigeria alone, for example, approximately 24 million people will shift out of endemic conditions of exposure to seasonal conditions by the 2030s (Figure 16).
- As would be expected, as temperatures warm (RCP 8.5 by the 2080s), considerably fewer people are affected as temperatures warm beyond the thermal threshold of mosquito-parasite survival.

Figure 15: Areas that are currently considered endemically suitable but will change to seasonally suitable for malaria under a changing climate across both RCP 4.5 and RCP 8.5 by the 2030s, 2050s, and 2080s

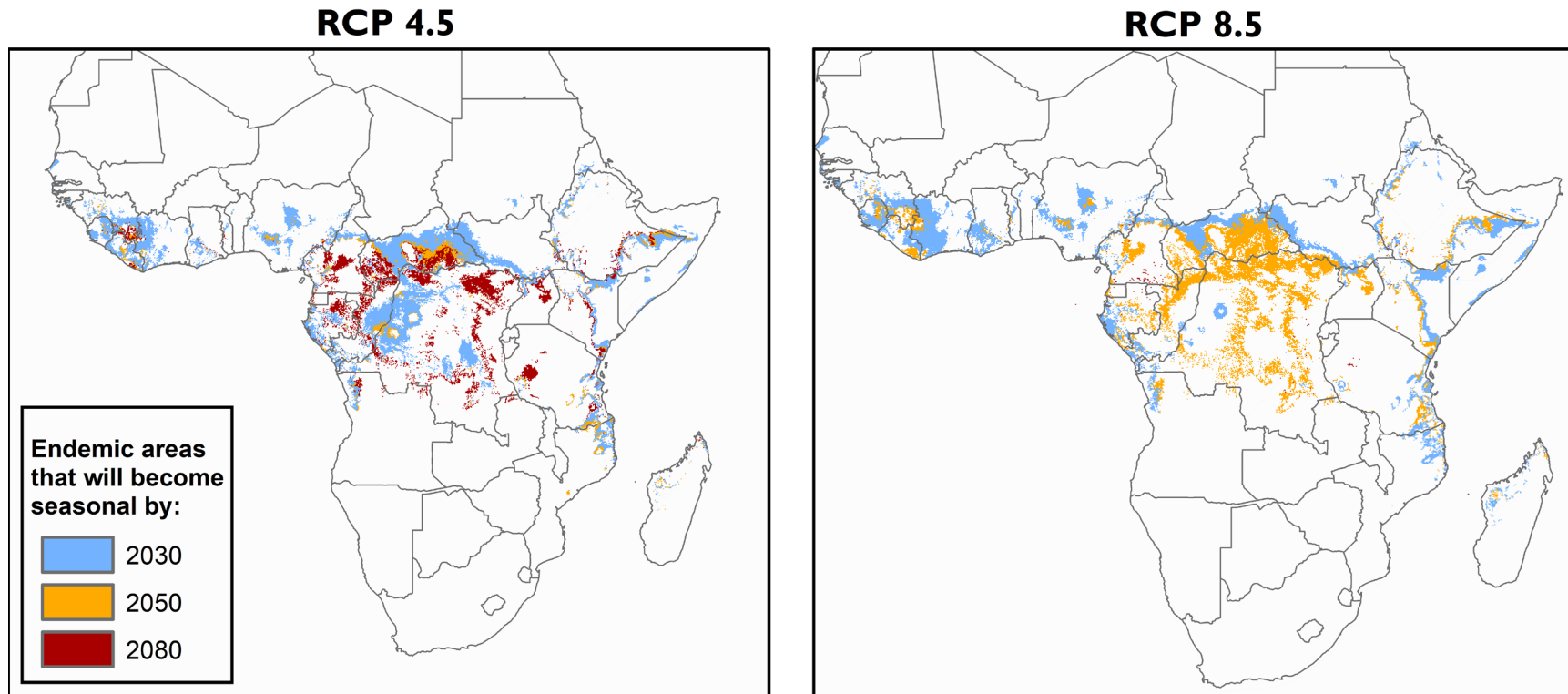
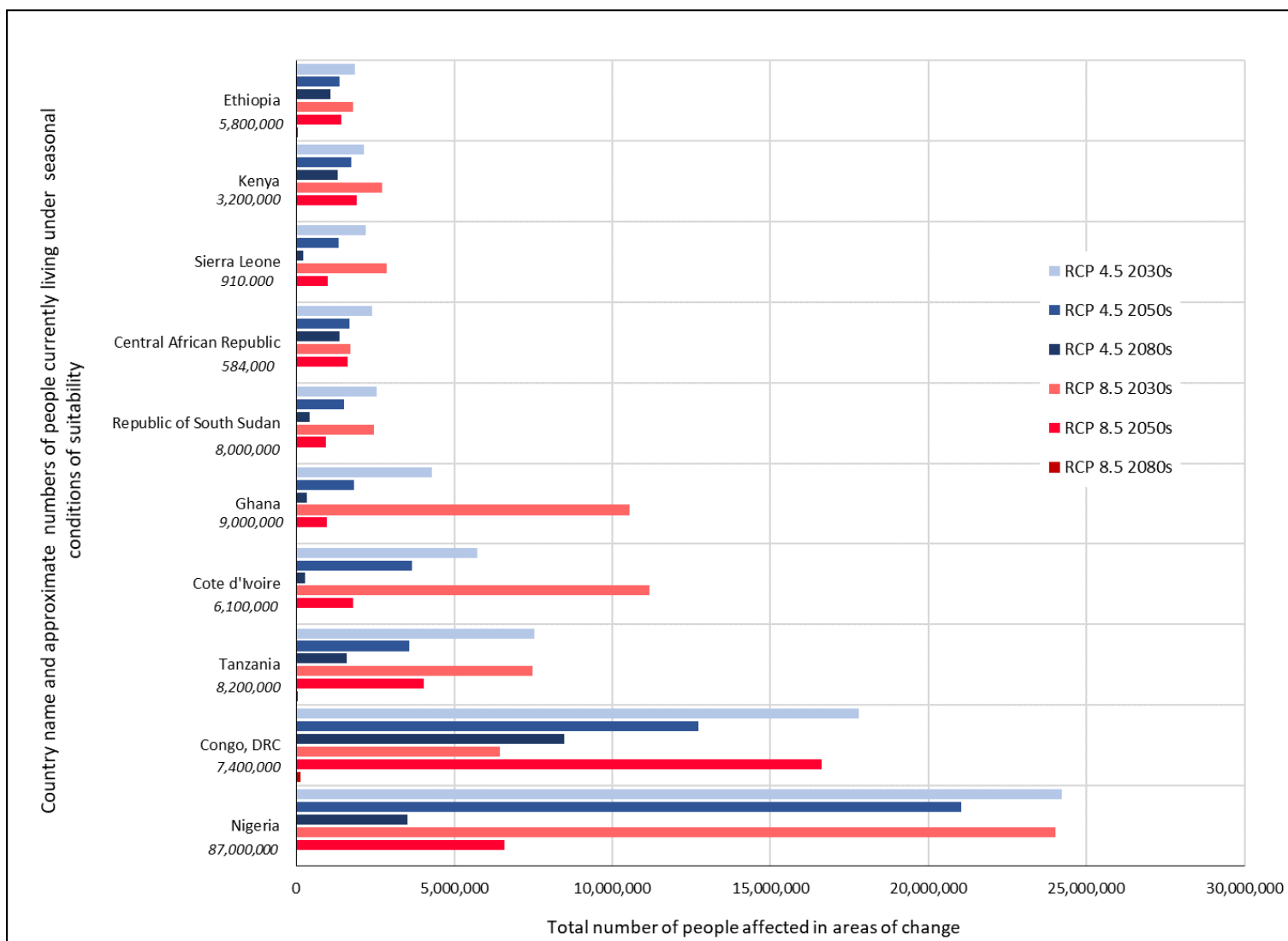


Figure 16. Number of people living in endemic conditions that will be living under seasonal conditions of suitability by the 2030s, 2050s, and 2080s under both climate futures evaluated (7-9 months per year)



Note: Top 10 countries in terms of numbers of people affected by the 2030s and RCP 4.5 are shown here. Approximate numbers of people living in seasonal conditions of suitability current are listed in italics below the country name on the vertical axis, for comparative purposes.

ASSUMPTIONS AND LIMITATIONS

The main limitations of this study include the following:

- It uses a temperature-only model.
- It does not directly measure the effect of rainfall on malaria vectors and parasites but uses the NDVI as a proxy.
- It does not explore the role of other environmental and social factors that could influence outcomes, such as migration, changes to landscape, and new technologies to control malaria vectors.
- It relies on uncertain population projections to estimate the number of people at risk for changes in malaria suitability beyond 2020.
- There are inherent uncertainties in all climate model projections.

TEMPERATURE-ONLY MODEL

The aim of this study is to offer broad geographic insights on the influence of the key variable of temperature on malaria suitability. Other factors, such as rainfall, the built environment, and migration, can also influence suitability, especially at smaller scales (Thomson et al. 2005, Coetzee et al. 2000). The role of these other drivers will be addressed by subsequent predictive studies on a geographically more local scale.

All of the life-history traits of the Anopheline mosquito and the *Plasmodium* pathogen in the model are temperature dependent, and thus temperature limited (Mordecai et al. 2013). Clearly, there are other variables that play a role in survival, but the role of temperature cannot be overstated. The traits in the model are based on precisely measured laboratory data. This ensures that the nonlinear model plots were based on temperature relationships at constant temperatures (Mordecai et al. 2013). That is, we used monthly means rather than daily fluctuations (Ryan et al. 2015).

The model also assumes that the relationship between the mosquito and pathogen life cycles will remain consistent as climates change because we cannot currently capture explicitly in the lab or in a model the effects of climate and temperature changes on malaria-infected Anopheline mosquitoes. Laboratory research should conduct temperature variability experiments to fully understand this relationship.

SPECIES SWITCHING

The potential for species switches with temperature changes is not considered in the model. The model projects effects on Anopheline mosquitoes (*Anopheles gambiae*), and *Plasmodium falciparum* malaria parasites because this is the primary vector-parasite pairing currently of concern in Africa. However, the *Anopheles gambiae sensu lato* mosquito is a species complex of eight morphologically indistinguishable species—*An arabiensis*, *An bwambae*, *An melas*, *An merus*, *An quadrimaculatus*, *An gambiae sensu stricto*, *An coluzzii*, and *An amharicus*—that occupy different regions or habitats (Coetzee, M. et al. 2000; Coetzee, M. et al. 2013; Hunt, et. al 1998). They are therefore subject to different climate pathways. We would need measurements of their responses to changes in temperature to project the species that would become more or less dominant and the expansion or contraction of their habitats.

In addition to *Plasmodium falciparum*, *P. vivax* (Mendis et al. 2001; Liu et al. 2014), *P. malariae*, and *P. ovale* are present in most endemic malaria regions. These species have been recognized for centuries, but they have been overlooked in Africa because they are less prevalent, cause lower case-fatality rates, or are only a major cause of morbidity in other parts of the world. They may, however, create complex coinfections of malaria (Mueller et al. 2007).

There are also emerging and establishing spillover malaria species, primarily from primate populations. While mainly associated with human cases in Southeast Asia (Cox-Singh et al. 2008; Singh and Daneshvar 2013; Wilson, et al. 2011; White, et al. 2008), are found in old-world monkeys, and after recognition a decade ago, has been counted as the fifth human malaria species. In Africa, great apes have been associated with several human and related malaria species (Duval et al. 2010), suggesting a source of emergent novel strains. As human populations migrate, encountering new habitats or moving strains among continents, we cannot identify the strains that may become important in Africa.

RAINFALL

Measured as precipitation falling in a month or any other time interval, rainfall is hard to translate into suitable Anopheline habitat at large scale because it is highly variable in:

- How it falls: Whether, for example, in high volume over short periods or constant volume over a longer period.
- How it accumulates: Whether it is absorbed into vegetation, stands in puddles, or runs off roofs into gutters.
- How it persists: Whether in saturated tree holes, washouts, flooding, or scouring.

Intense rainfall events can wash away breeding sites (USAID 2018), and too little rainfall can limit mosquito survival. The model addresses the effect of too little rainfall by excluding populations in areas that are too arid for mosquito survival.

Because projections of rainfall are uncertain at the geographic scale of this analysis, we adapted the method, similar to Ryan et al. (2015), that was presented by Suzuki et al. (2006), using NDVI to describe moisture in the habitat conducive to mosquito breeding. We took more

recent years (2016–2017) for NDVI values than Suzuki et al. to create an “aridity mask” – that is, a raster map describing areas too dry for too long for mosquitoes to survive and breed within a year. We looked at the consecutive monthly NDVI values by map pixel in 2016–2017, and areas where the NDVI was less than 0.125 for two or more consecutive months were deemed too dry for mosquitoes to start breeding. This is a conservative approach, as it means we do not exclude areas that may have irrigation, which maintains suitable habitat beyond rainy seasons or creates habitat where no rain falls in temperature-suitable months.

Using NDVI, however, constrains our projections because there are no future NDVI measures. Therefore, we include a current, average climate year data set in our projections. While we do not expect the aridity mask to remain static into the future, it nonetheless provides a conservative approach again. We expect warming in the areas of interest to this study, and by using a masking approach, we may exclude *less* area than will become too arid and overestimate the suitable areas for mosquito habitat, provided that changes in rainfall do not counter the effects of changing temperatures. In fact, the areas that would naturally dry out in the future and become part of an aridity mask could have water brought in, such as through irrigation, and thus remain suitable to malaria. This is largely why the NDVI approach to describing suitable habitat for Anopheline mosquitoes is such a promising research avenue.

OTHER ENVIRONMENTAL AND SOCIAL FACTORS

MIGRATION

In this study, we are limiting the implications of the temperature suitability model for malaria to a mean world outcome and simply describing a risk to projected populations in a world of projected increasing mean monthly temperatures. People will respond to climate shifts in a variety of ways that will influence their exposure to malaria. For example, they may migrate after too many near-drought years that make farms unprofitable, or because of violent conflict over water rights (Baldwin, et al. 2014; Bettini 2014; Burkett 2011; Locke 2009; Methmann and Oels 2015; Reuveny 2007). We also are not accounting for urbanization beyond our population projections. If more people move to cities than projected in this study, the size of the population at risk for malaria will be smaller than model projections. Added to this, people’s behaviors in urban areas may differ from that in rural areas and affect their exposure. For example, they may spend less time outdoors in the mosquito habitat. Mosquito control strategies (e.g., access to indoor residual spraying and insecticide-treated bed nets) may also differ.

CHANGING LANDSCAPE

We also have not captured changing landscape, that is, anthropogenic land use change and climate-driven landscape and landcover change. Large-scale agricultural conversion will affect the suitability of habitat for mosquitoes. For example, there is an association between forest cover loss and malaria increase (Vittor et al. 2006; Yasuoka and Levins 2007; Afrane et al. 2008; Lindblade et al. 2000), and, as mentioned above, irrigation can provide moisture not projected by rainfall patterns. As forests continue to disappear, the types of mosquitoes in those areas will change. There may be shifts in Anopheline species dominance as tree-hole breeders lose habitat with deforestation or slash-and-burn agriculture, and puddle breeders gain

dominance. Mosquitoes that prefer to bite humans (anthropophilic) may displace species that prefer to bite animals (zoophilic), or people can increase their risk by grazing cattle and goats on the land and allowing two mosquito species to persist.

NEW CONTROL AND TREATMENT STRATEGIES

We have not included novel control strategies in our model. New gene drive technologies (Eckhoff et al. 2017; Hammond et al. 2016; Windbichler et al. 2011) and other approaches being studied (Kumar et al. 2007; Wells et al. 2009) could decrease large populations of Anopheline mosquitoes within a single generation (e.g., less than a year). Drug breakthroughs for malaria will also change the risk landscape, as will drug-resistant malaria strains (Artzy-Randrup et al. 2010; Burki 2009; Dondorp et al. 2009; Klein 2013; malERA Refresh Consultative Panel on Insecticide and Drug Resistance 2017; White 2004; Zhou et al. 2017; Jones et al. 2012). When the parasite becomes resistant to a drug, it can only dominate in a human population that continues to use that drug. Over time, however, use of the drug has been found to make the parasite less fit. For example, chloroquine resistance is becoming less pronounced in the parasite, which means that it could now be used effectively in treatment, whereas 20 years after introduction, resistance made the drug ineffective. However, the timescales at which resistance selection arises and falls in the human population is not predictable, and thus is not included in this modeling study.

Additional climate-mediated impacts not included in this model include other vulnerabilities or potential worsening chronic conditions, such as asthma (Beggs and Bambrick 2005; Cecchi et al. 2010; D'Amato et al. 2015; Sheffield et al. 2011), diabetes (Luber and McGeehin 2008; Balbus and Malina 2009), and heart disease (McMichael and Lindgren 2011).

Added to these are more frequent extreme events such as heat waves (Luber and McGeehin 2008), lightning (Price and Rind 1994; Liang et al. 2017), flash flooding (Hallegatte et al. 2013), and drought (Dai 2012). These climate-mediated impacts present a new complexity of risk that should be included in future modeling.

POPULATION PROJECTIONS BEYOND 2020

The projections of the number of people affected by changing malaria suitability are derived from the Gridded Population of the World (GPW) version 4, which is tied to UN projections and is only available to 2020. These are also the only population datasets that do not incorporate the effects of environmentally related variables (e.g., land cover, night lights). We use this dataset to avoid the confounding effect of double counting environmental variables both in the population projections and in the vector modeling. This introduces two limitations to the study:

- As with climate models, the population projections do not necessarily capture all the factors that drive population movement.
- Because population projections to 2030, 2050, and 2080 are not available without incorporating environmental variables, we extrapolated from the GPW 2020 projections.

Thus, the estimates of population at risk should be taken as best modeled estimates rather than exact values.

CLIMATE MODEL UNCERTAINTIES

While substantial progress has been made in recent years in climate projections, decision makers should be aware of the uncertainties inherent in modeling before choosing climate policies or measures. These uncertainties include:

- Imperfect scientific knowledge and the computational constraints of modelling regional detail while still incorporating relevant large-scale climate patterns
- Events that are difficult to predict but that can have large climatic consequences: single events (e.g., crossing a temperature or rainfall threshold), recurrent events (e.g., the return period of a flood), the frequency and intensity of discrete, high-impact events (e.g., hurricane frequency), and complex events (e.g., drought, which results from the interplay of several factors).

Recognizing these uncertainties, we employed good practice by incorporating a multimodel range of climate projections rather than a single model, as discussed above.

CONCLUSIONS AND INSIGHTS FOR ACTION

This analysis offers a new, initial view of potential changes in malaria seasonality due to projected rising temperatures. Nevertheless, this study alone is not meant to guide programmatic decisions. Additional field studies are needed for these findings to be used as predictive insights, and it is important to consider the role of temperature as a driver of malaria burden when combined with many other likely drivers.

Addressing the changing risk profile of malaria due to temperature increases combined with other drivers will require modifying current interventions and programs, and potentially implementing new programs, that can adapt and respond to changing climate conditions. With these challenges come opportunities for improving observations, surveillance, and responses, including detailed geographic targeting, optimizing strategies (e.g., finding the right combination of vector and case management), and aligning interventions to changing seasonality. Some of the implications of this research for action and decision-making are discussed below.

TARGET ON-GROUND SURVEILLANCE AND RESPONSES TO CHANGING EPIDEMIOLOGY

There are many examples across sub-Saharan Africa where investments have shown marked progress in malaria control strategies. These gains, however, could be compromised if future investments do not consider the role of rising temperatures in changes to epidemiology. The analysis presented here offers several insights of relevance to these risks:

- Targeted and informed on-the-ground surveillance: Knowing where and when changes in burden are likely to take place offers the opportunity to geographically target monitoring programs with the goal of guiding interventions to achieve the highest impact with limited resources.
- Addressing the risk of epidemics: Where malaria suitability is likely to shift from nonexistent to newly suitable, whether seasonal or endemic, the risks are critical. When local populations have little or no immunity to the disease, malaria suitability changes can often lead to epidemic conditions, especially among vulnerable groups such as pregnant women, children, and the elderly. Surveillance data allows for the preparation of a timely response before the outbreak of epidemics and can guide decisions around distribution of malaria services and their use by impacted communities.
- Adjusting current management and control interventions: Surveillance information offers an opportunity to adjust the investment time frame (seasonal to year-round, or vice versa), optimize vector control, and improve case management, with the evidence base

to support these actions. Pinpointing regions where transmission could be reduced lowers the cost of interventions and provides an opportunity to reach pre-elimination or elimination.

- Addressing malaria elimination: In areas where the months of malaria suitability will decrease, the opportunity exists to invest in targeted surveillance and response systems to identify, track, and respond to malaria cases in remaining transmission foci (e.g., infected mosquitoes or affected patients).

IMPROVE A COUNTRY'S CAPACITY FOR COLLECTING AND USING INFORMATION AT THE NATIONAL LEVEL

Significant progress has been made to improve data and information available for malaria programming, management, and evaluation via investments made to strengthening routine disease reporting and health management information systems. Nevertheless, challenges remain, including the need to improve reporting rates and to shorten the lead times to inform planning and monitoring to near real-time.

Understanding how rising temperatures could impact vector ranges, and thus have the potential to alter disease dynamics, is an important first step to building the knowledge base required to evaluate how climate may impact malaria incidence and inform investments. This analysis indicates that, as temperatures rise, even by around 2030, important changes are anticipated in *Anopheles* transmission suitability, both in changes in seasonality and range of malaria vectors. Importantly, temperature-driven changes in vector dynamics are themselves mediated by direct and indirect environmental and societal factors, such as changes to ecosystems, land use, and others that may reduce or amplify the vulnerability of certain groups to malaria risks. New methods of data collection, integration, and analysis will require cross-ministry investment, information-sharing, and analysis to perform, and will be critical to inform understanding of the complexity of the links between these factors.

Public health observatories, many already operational around the world, could provide a model for how to scale up analysis of health data in the context of other climate and environmental parameters. In general terms, health observatories are virtual platforms that can link health systems to other information of relevance, such as weather data, to support health policies and planning. According to the WHO (2016), "their purposes vary but the major objectives are: monitoring health situations and trends, including assessing progress toward agreed-upon health-related targets; producing and sharing evidence; and supporting the use of such evidence for policy and decision making." Such observatories could also help in the timely use of remotely derived weather and climate information to inform investments and strategies in malaria control.

Establishing a health observatory in countries where malaria patterns are changing rapidly could:

- Formalize agreements around interdepartmental and inter-ministerial collaboration and data sharing: Governmental health agencies often lack the mandate to collaborate and share data with other stakeholders. However, in order to make meaningful advances on research and monitoring to understand climate and weather impacts on epidemiology, it is essential to have access to historical climate and trend information, together with health data related to past events. Improved communication, collaboration, and information sharing across sectors will be critical to strengthening understanding of vector changes and rapidly evaluating the potential risks from specific weather events to a country, region, or health post.
- Leverage information technology: Gains in GIS and the development of other tools can support efforts to scale as well as to fine-tune analyses focused on improving the timeliness and completeness of surveillance during critical periods.
- Build a community of practice: It will be critical to go beyond the traditional program partners to integrate partners who could explore the links between environmental parameters of interest (including weather and climate) and strategic and programmatic decisions that need to be made in a malaria program.
- Advance research on critical outstanding questions with respect to the use of climate information to inform malaria planning: Research priorities include, but are not limited to, understanding more fully the links between increased temperature, changing rainfall patterns, extreme weather events, and malaria; determining specific climatic thresholds of concern for surveillance; and improving analytic tools to visualize cross-sectoral information.

BUILD CAPACITY IN HEALTH SYSTEMS

In spite of the significant advances made in many parts of sub-Saharan Africa in reducing malaria incidence and outbreak, weak health systems—including understaffed health posts, lack of skilled human capacity, and unreliable supply chain management across the spectrum of services and programs—slow progress toward malaria control goals and targets. For malaria programming and health services to respond to climate risks, investments need to be made in building the skills and capacity of health workers to understand and address the health risks posed by climate. This includes:

- Training health workers on the links between health and climate change: Many public health workers and leaders are ill-equipped to face the challenges of climate risks and lack an understanding of how health service delivery will need to change. The uptake and use of early warning systems, educational and advisory systems for disseminating clinical guidelines, and even the guidance offered by community health workers will all require building awareness of the risks and responses available to address climate phenomena.

- Streamline supply chain management: Especially in countries where malaria control interventions have been successful, supply chain management will need to be streamlined to guarantee the delivery of commodities and services for remote and mobile populations.
- Promote research on applied, service-oriented health services questions: The lack of service-oriented research to drive regional health service development for climate change has potentially serious implications for future control efforts.

REFINE COUNTRY SELECTION AND STRATEGIC BUDGETING FOR INTERNATIONAL PROGRAMS

The potential impacts of increased temperature on malaria burden are too great to be ignored during country selection and strategic budgeting. New country selection for international programs investing in malaria interventions is complicated and often dictated by many factors, including available funding, national capacity to implement programs, ability to work across agencies, and ability to work with country-specific partners, donors, and stakeholders. While there are many drivers of malaria burden at a national scale, this report demonstrates that increased temperature may contribute to putting large populations at risk of both seasonal and endemic malaria where the burden was previously significantly less. Because of this potential risk, it is important to include projected temperature increases during strategic discussions for country selection in the near and medium term.

The role of temperature in malaria burden in Gabon, for example, where more people are likely to be at risk of both seasonal and endemic malaria by the 2030s due to projected temperature increases, should be considered. Furthermore, temperature projections help to design interventions for populations that may be at risk in the next 10–12 years, potentially preventing large-scale national challenges.

DEVELOP REGIONAL APPROACHES AND PARTNERSHIPS

In addition to country selection, this report has implications for addressing malaria regionally. Some regions of Africa, such as higher elevation areas in Southern and East Africa and parts of Central Africa, will likely have increased burden. Part of the Horn of Africa and West Africa will likely have decreased burden. A regional approach to fighting malaria and regional partnerships and networks may improve strategic targeting and elimination efforts.

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